

Materials and Design

The Art and Science of Material Selection in Product Design

Third Edition

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Mike Ashby and Kara Johnson



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Preface

This third edition represents the culmination of many years teaching and researching the fundamentals and application of material science and material selection (Mike) and a few more years exploring ideas related to materials, materiality, and making—both with designers and in the context of the design industry (KJ). We have explored these ideas both in general and with specific reference to one material or one manufacturing process or one particular product design challenge. We hope that you enjoy this edition and that it provides a valuable reference both now and in the future.

With the success of the first two editions of this book and based on additional input from students, teachers, designers, and our own experiences, we have been encouraged to evolve the storytelling and the details of this textbook one more time in a third edition. With help from Willy and Patrick at Swayspace, we re-designed the cover to capture a more authentic merger of the words “materials” and “design.” We have included more IDEO perspective based on industry experience that one of us (KJ) has accumulated over the last 10+ years in order to illustrate not just a point-of-view about materials and design but also to introduce and define the role of materiality and making. Based on Mike’s recent work, there is a new chapter about sustainability and issues related to eco- and “green” design. The material and process profiles, too, have expanded once again to include more biopolymers and fibers and we have added some new photography in order to make them each more accessible and inspirational.

Books on material selection—and there are many—focus on finding a match between material properties, the technical requirements of a design, and the science of materials. There are now well-developed methods for doing this, supported by sophisticated software tools (Granta Design, CES). Together they form the basis for the teaching of material selection in engineering programs around the world. But these programs frequently ignore or at best devote little attention to what might be called the art of materials—the role they play in industrial design. This may be because the more technical aspects of engineering form a structured, analytical field that can be recorded and taught as a set of formal procedures. Design cannot so easily be formulated as a method; it relies instead on

Mike Ashby's Top Five

1. *The Material of Invention*—Intriguing descriptions of the role of material in “invention.” Manzini, E. (1989), ISBN: 0-85072-247-0.
2. *Experiences in Visual Thinking*—A very readable introduction to creative thinking and design. McKim, R.H. (1980), ISBN: 0-8185-0411-0.
3. *The Visual Display of Quantitative Information*—The bible of graphical methods for representing—and misrepresenting—information. Tufte, E.R. (1983), ISBN: 0-9613921-0-X.
4. *Designing Pleasurable Products*—A discussion of the design requirements of function, usability and pleasure. Jordan, P.S. (2000), ISBN: 0-748-40844-4.
5. *Design of Everyday Things*—A book that provides insight into the design of familiar products. Norman, D.A. (1998), ISBN: 0-385-26774-6.

Kara Johnson's Top Five

1. *Manufacturing Processes for Design Professionals*—The best reference available to get inside the factory. Thompson, R. (2007), ISBN: 978-0-500-51375-0.
2. *Ronan and Erwan Bouroullec (Works)*—An inspiring documentary of the Bouroullec brothers' design process and experimentation. Bouroullec, R&E and Koivu, A. (2012), ISBN: 978-0714862477.
3. *Haptic*—A collection of objects inspired by and made from paper. Takeo Paper Show (2004), ISBN: 978-4022579317.
4. *Suke Suke, Fuwa Fuwa, Zawa Zawa*—A collection of extreme manipulations of beautiful fabrics. Nuno Corporation, www.nuno.com.
5. *I Miss My Pencil*—A series of experiments in the senses, modern craft, love and fetish. Johnson, K. and Bone, M. (2009), ISBN 978-0-8118-6075-8.

“visual” thinking, sketching and modeling, an exploration of aesthetics and perception, behaviors and storytelling.

This book is about the role of materials and processes in product design. It complements an earlier text (by Mike) that develops methods for choosing materials and processes to match the technical requirements of a product: “Materials Selection in Mechanical Design.” Here, by contrast, the emphasis is on a wider range of the information about materials that designers need, the way they use it, and the reasons they do so. This book preceded but also complements a set of design experiments published a few years ago by Kara: “I Miss My Pencil.” These experiments were intended to inspire designers to think about objects and materiality as a form of storytelling within the context of the following categories: the senses, craft, love, and fetish.

The book has two audiences: students and working designers. For students, the purpose is to introduce the role of materials and manufacturing in design, using language and concepts with which they are already familiar. For working designers, the purpose is to present a concise reference source for materials and manufacturing, profiling their characteristics. To this end, the book is divided into two parts. The first presents ideas about mixing materiality and design, methods of material selection, and relevant case studies; the second is devoted to the profiles. Whether studying or working...this book is written for material scientists who want to know more about design, and for designers who want to know more about materials.

Many colleagues have been generous with their time and ideas. In particular, we are grateful for discussions, criticisms, contributions, and constructive suggestions from Professor Yves Brechet of the University of Grenoble; Dr. David Cebon, Dr. John Clarkson, Dr. Hugh Shercliff, Dr. Luc Salvo, Dr. Didier Landru, Dr. Amal Esawi, Dr. Ulrike Wegst, Ms. Veronique Lemercier, Mr. Christophe LeBacq, and Mr. Alan Heaver of Cambridge University; Dr. Pieter-Jan Stappers of the Technical University of Delft; Dr. Torben Lenau of the Technical University of Denmark; Jihoon Kim from IDTC and Nicolas Zurcher from IDEO for their photography; and Julie Christensen of Surface Design, San Francisco for her mentorship. We have included case studies from IDEO and we both deeply appreciate the opportunity to continue to work with IDEO to define and explore the role of materials and materiality in design and to unlock the culture of making stuff and making ideas real that is an inherently endless and amazing part of the design process. We also particularly

wish to acknowledge the contribution of Willy Schwenzfeier and Patrick Fenton of Swayspace, New York, to the design of the book itself. Many other people and organizations, listed on the following page, contributed images or gave us permission to reproduce their images and photographs of their products.

Mike Ashby and Kara Johnson, April 2013

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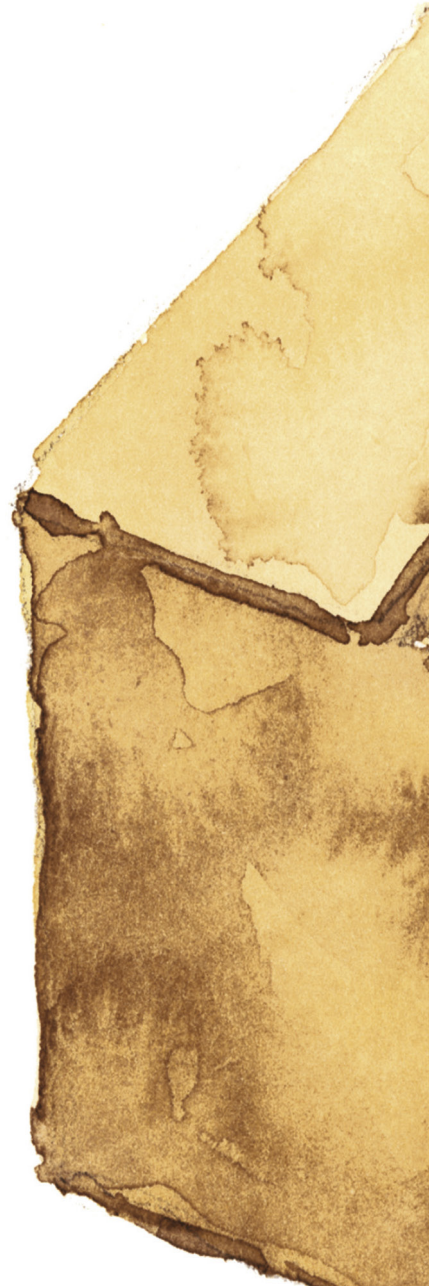
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This book includes ten chapters that explore how materials and design are connected. An understanding of materials and manufacturing (M&M) is a core element of the design process. It is our intention to build a solid foundation of information and knowledge around M&M and to encourage a passion for the exploration and manipulation of M&M in the context of design. This book is a practical guide for designers who want to know more about materials and for material scientists who want to know more about design. It is intended to inspire and teach.

In the appendix to these chapters, more detailed maps of technical information have been included for reference and exercises for students and working designers have been outlined for each chapter. Before we get to the end of the book, let's start at the beginning. In the first chapter, by way of introduction, Mike and KJ each share their own point-of-view on materials and design.



Chapter 1

Introduction

We live in a world of materials; it is materials that give substance to everything we see and touch. Our species – *homo sapiens* – differs from others most significantly, perhaps, through the ability to *design* – to make things out of materials – and in the ability to see more in an object than merely its external form. Objects can have meaning, carry associations, or be symbols of more abstract ideas. Designed objects, symbolic as well as utilitarian, predate any recorded language – they provide the earliest evidence of a cultural society and of symbolic reasoning. Some of these objects had a predominantly

functional purpose: the water wheel, the steam engine, the gas turbine. Others were (and are) purely symbolic or decorative: the cave paintings of Lascaux, the wooden masks of Peru, the marble sculptures of Attica. But most significantly, there are objects that combine the functional with the symbolic and decorative. The combination is perhaps most obvious in architecture – great architects have, for thousands of years, sought to create structures that served a practical purpose while also expressing the vision and stature of their client or culture: the Coliseum of Rome, the Empire State Building of New York, the Pompidou Centre of Paris, each an example of blending the technical and the aesthetic.

On a smaller scale, product designers seek to blend the technical with the aesthetic, combining practical utility with emotional delight. Think of Wedgwood china, Tiffany glass, Chippendale furniture – these were first made and bought to fulfill a functional

purpose, but survive and are treasured today as much for their appeal as objects of beauty. Think, too, of musical instruments: the inlaid violin or harpsichord; of weapons of war: the decorated shield or carved details in a gun; or of the weapons of the mind: the gilded pen, the illuminated manuscript. All of these are tools made in forms that express aspects of their creator's imagination and desire to make objects of delight as well as of utility (1.1 and 1.2).

1.1 Mixing Delightful Decoration and Utilitarian Function

The Stata Center at MIT (Image courtesy of Prof. John Fernandez, Department of Architecture, MIT, Cambridge, MA)





**1.2 Mixing Delightful
Decoration and Utilitarian
Function**

A Colt pistol

With respect to materials and design, it is the combination of elements of art and science that make it work. Materials are not simply numbers on a datasheet. And design is not a meaningless exercise in styling and it is not an isolated exploration of technology. What matters is the process of finding solutions that are meaningful to people, that enable new experiences and inspire and create positive impact in society and in our own daily lives. Today, people are looking for products that are sustainable and lovable, and it is the job of a designer to create those products. We need to evolve from an industrial society that is driven by consumerism to one that respects and admires materiality and efficiency. To explore materiality, we need to get inside the factory and meet the craftsmen and -women that make our products. To make decisions about efficient use of materials, a basic foundation of technical knowledge of materials and manufacturing is required. In combination, materiality and efficiency allow the designer to create products that are creative and yet

fully optimized tangible expressions of an idea. It is this idea that will go-to-market.

People – consumers – buy things because they like them – love them, even. To succeed, a product must, of course, function properly, but that is not enough: it must be easy and convenient to use, and it must have a personality that satisfies, inspires, gives delight (1.3). This last – personality – depends strongly on the industrial design of a product. When many technically equivalent products compete, market share is won (or lost) through its visual and tactile appeal, an exploration of other senses or emotional connection, the associations it carries, the way it is perceived, and the experiences it enables. Consumers now expect delight as well as function in everything they purchase. Creating it is a central part of design.

Advances in materials enable advances in industrial design, just as they do for technical design – together these advances allow new behaviors, new experiences, new architectures (1.4).

And here we need a word that requires definition: “inspiration” – the ability to stimulate creative thinking. New developments in materials and processes are sources of inspiration for product designers, suggesting novel visual, tactile, sculptural, and spatial solutions to product design. Examples drawn from the recent past are the ability to color and mold polymers to make bright, translucent shapes; the co-molding of elastomers to give soft, tactile surfaces; toughened and textured glass to create transparent walls and flooring; surface coatings that reflect, refract, or

diffuse light; carbon fiber composites that allow exceptionally slender, delicate structures – and there are many more. In each of these examples innovative products have been inspired by the creative use of materials and processes.

Thus materials have two overlapping roles: that of providing technical functionality and that of creating product personality. It is here that an imbalance becomes apparent. Technical designers have ready access to information of the sort they need – handbooks, selection software, advisory services from material suppliers – and to analysis and optimization codes for safe, economical design. Industrial designers express frustration, both in print and in interviews, that they do not have equivalent support. In higher education the same discrepancy appears: the teaching of the science and technical application of materials is highly developed and systematized, supported by numerous texts, software, journals, and conferences; there is no similar abundance of support for the teaching of materials in industrial design.

Bridging this gap in information and methods is not simple. The technical terms used by engineers are not the normal language of industrial designers – indeed they may find them meaningless. Industrial designers, on the other hand, express their ideas and describe materials in ways that, to the engineer, sometimes seem bewilderingly vague and qualitative. The first step in bridging the gap is to explore how each group “uses” materials and the nature of the information about materials that each requires.



1.3 Function, Use, and Personality

A bicycle must function (wheels, chain, gears), be designed for use (to carry stuff from one place to another), and have a personality that fits its owner (decoration on the frame, handlebar tape).

The second is to explore methods, and, ultimately, design tools, that weave the two strands of thinking into a single integrated fabric. That, in two sentences, is what this book is about.



1.4 A Virtual Violin

The form of the violin is an essential part of its personality. In this electronic violin, the ghost-like form both makes the connection to the original and suggests the transmutation that has taken place. (Image courtesy Yamaha Corp.)

Kara Johnson: After more than 10 years working in the design industry, my perspective on how materials is part of the design process has shifted from materials and materiality to experimentation and storytelling. In the first few years, I was focused on how to inspire designers to use new materials and to use old materials in new ways. For the products we were designing, we considered inspiration and then selection as we moved from the beginning to the end of the design process. Across all the industries that we worked, we needed to consider a wide range



of materials – plastics, metals, ceramics, and natural materials – and a similarly wide range of manufacturing processes to manipulate each one. This set of materials and processes are included in the back of the book as a reference for any working designer. The level of detail included is intended to get you up to speed, get your feet wet, get you ready to ask more questions, and to help you to learn and inspire yourself and others. The right conversation with your design team, your client, vendors, and the factory who will make you what you are designing will be what makes you more likely to find the best solution to your specific design challenge.

In the next few years of work, as designers we started to explore how materials could play a role in brand and business strategy, the role of materials was about the connection that products have with people and how the materiality of an object plays a role in that emotional and physical connection.

Our consideration of materials stretched from product to space to digital or service experiences. Materiality is an idea that includes the following: a living hinge made of molded felt, the structure of expanded polystyrene bead packaging, the rust colored primer that paints the Golden Gate Bridge, patina on copper and any other surface, the texture and pattern of pixels, knit graffiti on the streets of London, the sweet smell of molded bioplastics. In industry, we see the same ideas represented in real ways – Nike’s first knit shoe and delicately molded sections of EVA for barefoot running, the fabric-wrapped “Gina” car and a flaming surface of pinched metal from BMW, an indestructible surface of Gorilla Glass™ on the iPhone or the brushed metal digital surface on iTunes first software release.

After building a connection between people and products, the idea of materiality had become ingrained in our design process and each designer had the tools

necessary to think about it and talk about it (internally or externally). Over the next few years, the role of materials in the design process stepped forward to include the idea of experimentation. It became evident, that in a highly constrained world of materials, manufacturing, and design – where cost constraints, technical limitations, or sustainability concerns sometimes drive the final selection of materials – we needed to force ourselves to jump ahead of the curve. We needed to experiment early in the design process in order to break the rules, to see what's possible and to find new constraints. Experimentation is a natural part of the design process. With a wide palette and an open mind, we attempted to build our ideas outside of the boundaries of typical industry constraints: a printer wrapped in felt, a bottle made of cork with a glass top, a perfectly machined black micro-camera. We wanted to use materials to build our ideas and provoke a conversation about the stuff that surrounds us and in some way shift the conversation about how we design, what we design, and how we talk about it. We want to use materials to tell a story.

Looking forward, over the next 10 years, the following three themes will drive the work that we do as designers and influences the role of materials: (1) the resurgence of making and the maker movement, (2) a global market that drives exploration of what it means to be made in a particular place/geography, and (3) the search for a more tangible way of thinking about, talking about, and doing brand.

We are all participating in some way in the maker movement. The maker

movement is present in low-volume craft (on the pages of www.etsy.com) to high-volume industries and in between (www.kickstarter.com) with a focus on both physical and digital platforms, for the sake of artistic expression and commerce.

In an economy that cares equally about what is global and what is local, the place where a product comes matters. This sense of place has highlighted the brand name of each country, city where stuff is made. Would you rather buy a product Made-in-Korea or Made-In-Japan? Do you know the difference? Does it matter? Apple's products are Designed-In-California, Made-In-China. It's part of their story. What is Made-In-Iran? What is Made-In-Williamsburg? Where is Williamsburg? The story and the meaning of each place and how the culture of making has evolved has and will influence the design process more and more as we want to fall in love with products and stories that are global and local.

What if your brand is made in the factory? What if the choices you make about fabric, metal, or plastic; injection molding, welding, or stitching – matter as much as the tagline, celebrity endorsement, or logo you choose. Your brand is manufactured, not managed. Your brand is a sum of the signature moments you create where people can physically connect to your brand. Your product is your story, your story is your product. The strategy isn't finished until the design is. For some companies, in some industries, for some consumers, brand is built from the inside-out (1.5), from material to product to identity and digital experiences to systems and the

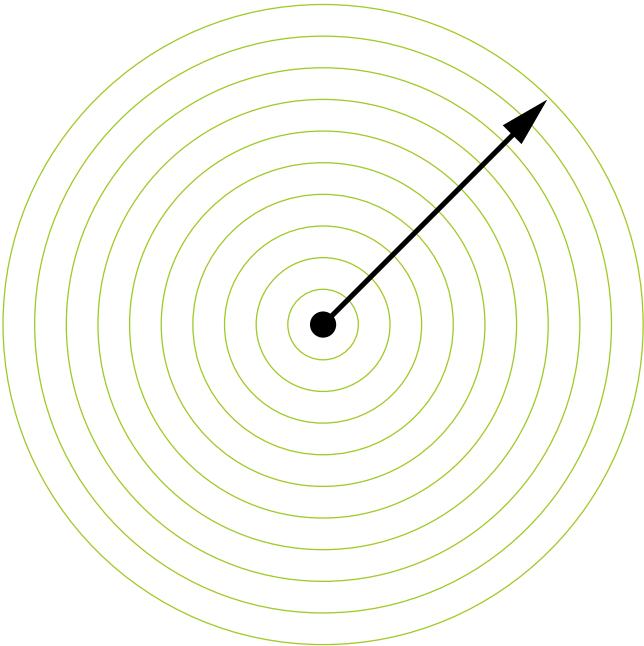
organization. When brand is built from the inside-out, elements of materiality and making matter most. Design plays the role of connecting materials to a bigger story.

This book is about the core ingredients of product design – materials are the ingredients designers use to imagine, create, and

modify an idea so that when it is made it becomes more than an object or a product, part of a bigger system of storytelling and experiences. We want to inspire and guide designers to build something that is extraordinary and iconic, something that has its own voice, its own story.

1.5 Built Brand

Building brands with a focus on product...from the inside-out...starting with materials as the key ingredient to a complete (36) brand experience.



- Brand**
- Organization**
- Systems**
- Service**
- Digital**
- Retail**
- Identity**
- Packaging**
- Product**
- Material**

Mike Ashby: There are three kinds of materials-related books with a design focus. The first are inspirational, relying on images to showcase materials, accompanied by text that expresses the emotional and aesthetic response of the writer. The second are books on material selection in engineering design, developing systematic methods of matching material choice to the mechanical thermal, electro-magnetic, and environmental constraints set by the technical requirements of the design. The third – of which this book is an example – seeks to connect and blend the approaches of the other two.

My background is in physics, materials science, and engineering colored by an itinerant history – early schooling in Australia, later in Manchester, England, then Belfast, Northern Ireland, University at Queen's University, Belfast, then Cambridge, England, 3 years in the Institut für Metalphysik, Göttingen, Germany, nine in the Division of Applied Physics at Harvard, Cambridge, Mass, then back to Cambridge, England, in the Engineering Department, together with a 3-year visiting professorship at the Royal College of Art in London, UK. Switching environments has its challenges – even in this connected world,

there are embedded cultural values in each location that differ from those you know. It teaches you how to observe (if only to help you acquire protective camouflage), to listen to unfamiliar points of view expressed in unfamiliar ways, and to look for overarching concepts rather than fine detail.

This background hardly qualifies me to write about Industrial Design, but here Kara's fascination with design and unquenchable enthusiasm provided complementary stimulus together with access to designers both in the UK and the US. The collaboration, somehow, produced this book.



Further Reading

There is a considerable literature on product design, some of it comprehensible, some not. Useful sources are listed, with ISBN number and a brief commentary, at the end of each chapter. Those listed below are a good starting point.

Baxter, M. (1995) “Product Design,” Chapman and Hall, London, UK. ISBN 0-7487-4197-6. (This ambitious book, which aims at an understanding of the entire product design process, covers design for appearance, for manufacture, for low cost, for reliability, and for environmental responsibility. A useful introduction, written in simple language.)

Clark, P. and Freeman, J. (2000) “Design, a Crash Course,” The Ivy Press Ltd, Watson-Guptil Publications, BPI Communications Inc. New York, NY, USA. ISBN 0-8230-0983-1. (An entertainingly-written scout through the history of product design from 5000 BC to the present day.)

Coates, D. (2003) “Watches Tell More than the Time,” McGraw-Hill, New York, NY, USA. ISBN 0-07-136243-6. (An analysis of the aesthetics, associations and perceptions of products past and present with examples, many drawn from automobile design.)

Dormer, P. (1993) “Design since 1945,” Thames and Hudson, London, UK. ISBN 0-500-20269-9. (A well-illustrated and inexpensive paperback documenting the influence of industrial design in furniture, appliances, and textiles – a history of contemporary design that complements the wider-ranging history of Haufe (1998), q.v.)

Forty, A. (1986) “Objects of Desire – Design in Society since 1750,” Thames and Hudson, London, UK. ISBN 0-500-27412-6. (A refreshing survey of the design history of printed fabrics, domestic products, office equipment, and transport system. The book is mercifully free of eulogies about designers, and focuses on what industrial design does, rather than who did it. The black and white illustrations are disappointing, mostly drawn from the late 19th or early 20th centuries, with few examples of contemporary design.)

Haufe, T. (1998) “Design, a Concise History,” Laurence King Publishing, London, UK (originally in German). ISBN 1-85669-134-9. (An inexpensive soft-cover publication. Probably the best introduction to industrial design for students (and anyone else). Concise, comprehensive, clear, and with intelligible layout and good, if small, color illustrations.)

Jordan, P.S. (2000) “Designing Pleasurable Products,” Taylor and Francis, London, UK. ISBN 0-748-40844-4. (Jordan, Manager of Aesthetic Research and Philips Design, argues that products today must function properly, must be usable, and must also give pleasure. Much of the book is a description of market-research methods for eliciting reactions to products from users.)

Julier, G. (1993) “Encyclopedia of 20th Century Design and Designers,” Thames & Hudson, London, UK. ISBN 0-500-20261-3. (A brief summary of design history with good pictures and discussions of the evolution of product designs.)

Manzini, E. (1989) “The Material of Invention,” The Design Council, London, UK. ISBN 0-85072-247-0. (Intriguing descriptions of the role of material in “invention” – here meaning creative design. The translation from Italian uses an interesting vocabulary, one unusual in a text on materials, and gives a commentary with many insights.)

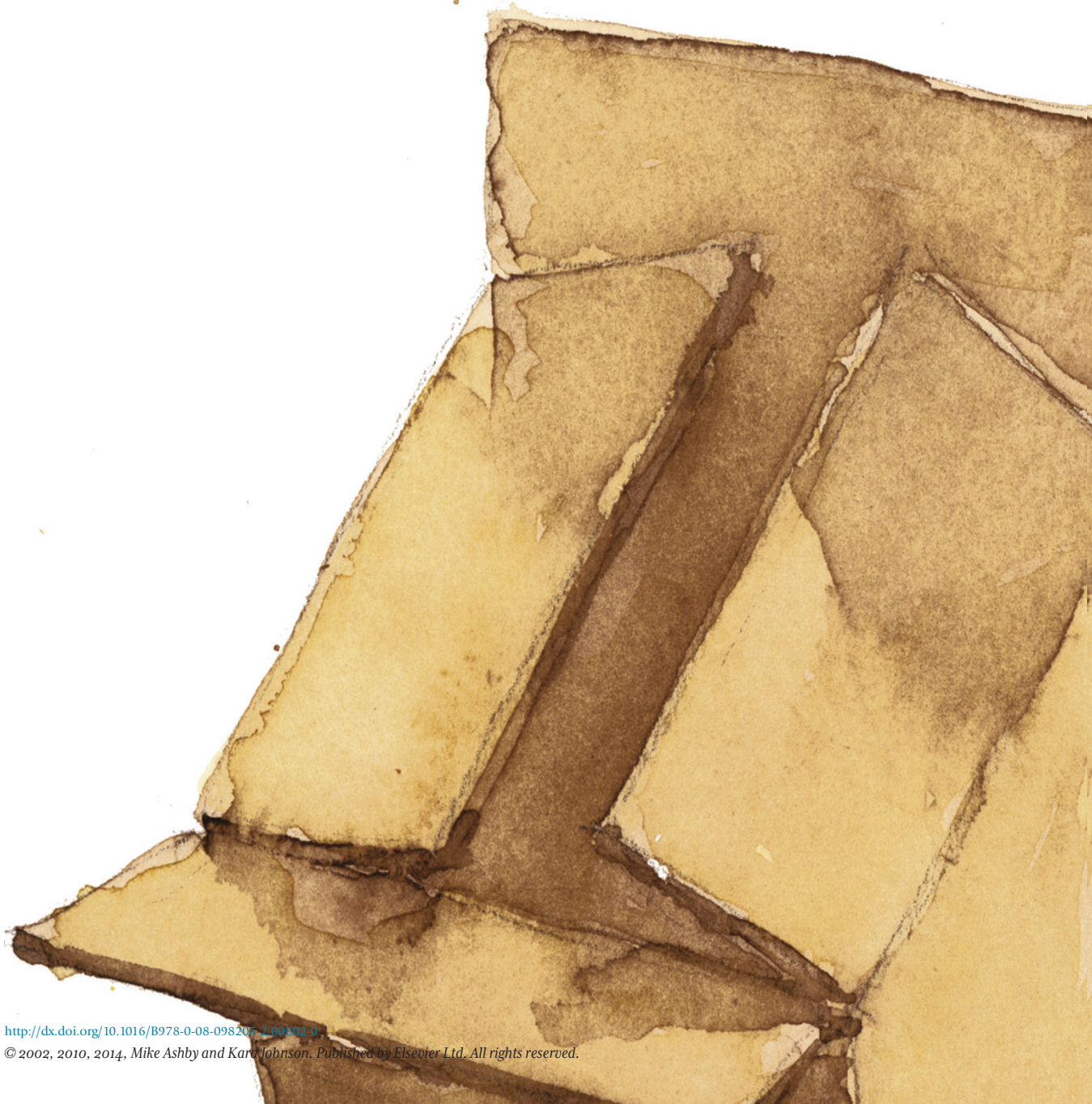
McDermott, C. (1999) "The Product Book," D & AD in association with Rotovision, UK. (50 essays by respected designers who describe their definition of design, the role of their respective companies and their approach to product design.)

Norman, D.A. (1998) "The Design of Everyday Things," MIT Press, London, UK. ISBN 0-385- 26774-6. (A book that provides insight into the design of products with particular emphasis on ergonomics and ease of use.)

Vezzoli, C. and Manzini, E. (2008) "Design for Environmental Sustainability," Springer-Verlag, London, UK. ISBN 978-1-84800-162-6. (A book co-authored by the writer of "The Materials of Invention" describing tools and strategies for integrating environmental requirements into product development.)

Chapter 2

What Influences Product Design?



Nothing is static. Today's designer seeks to optimize a design to best meet the needs of today's markets, but before the optimization is complete, the boundary conditions – the forces that influence the design decisions – shift, requiring re-direction and re-optimization. It is helpful to be aware of these forces; they create the context in which design takes place.

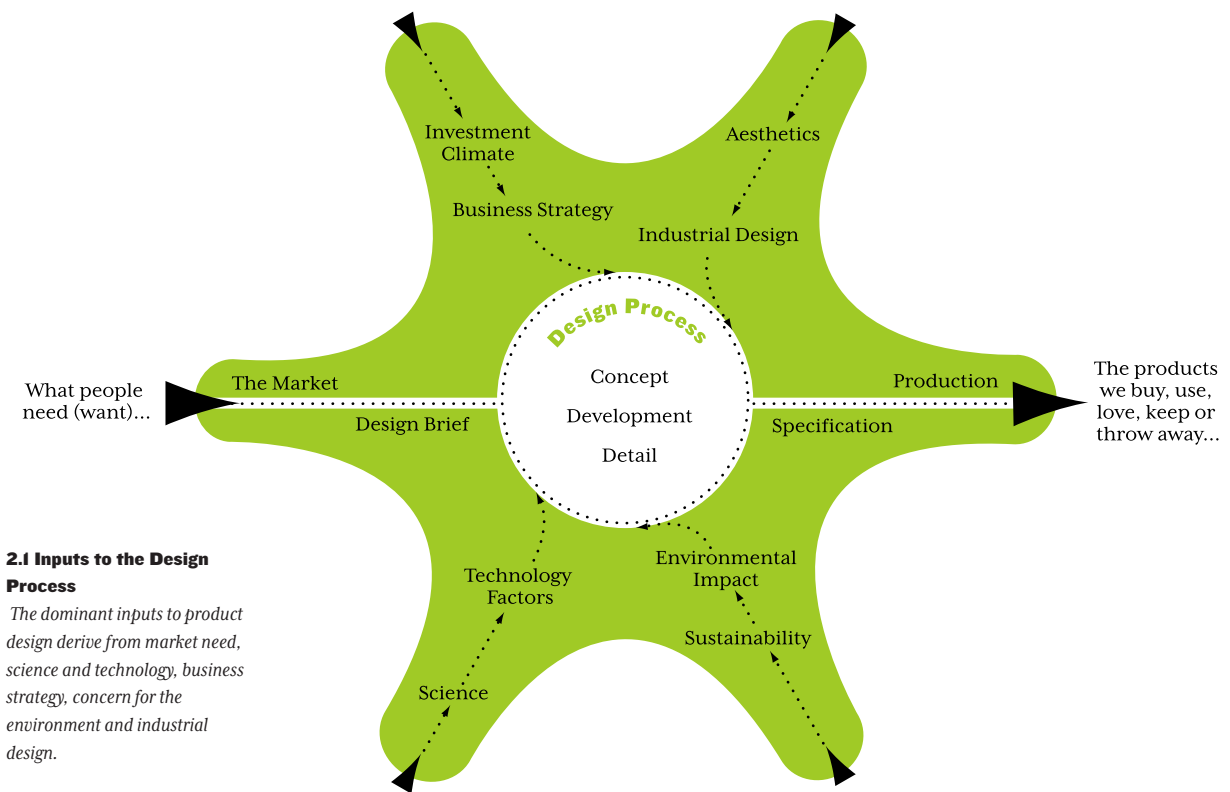
Figure 2.1 suggests five – the market, technology, investment climate, the environment, and industrial design. It is a simplification but a useful one. The central circle represents the Design Process, the workings, and dynamics of which we explore in Chapter 3. It is subject to a number of external influences, indicated in the surrounding branches. A good designer is always alert to developments in technology, deriving from underlying scientific research. New technology is exploited in ways that are compatible with the investment climate of the company, itself conditioned by the economic conditions within countries in which the product will be made and used. Concern to minimize the ecological burden created by engineered products heightens the awareness of design for the environment, and, in the longer term, design for sustainability. And, in the markets of the 21st century, consumers want much more than a product that functions well and at an affordable price; they also want satis-

faction and delight, making inputs from industrial design and aesthetics a high priority. There are of course many more influences, but discussions with designers suggest that these are currently among the most powerful. And, of course, they frequently conflict.

Before launching into the main development of the book, we briefly examine each of these influential forces, all of which thereafter lurk in the background, reappearing in later chapters when their importance makes itself felt.

People and the Market

Present-day economic growth and prosperity, both national and personal, and the nature of free-market economies make the market a powerful driver in product design. In a developed country many products are technically mature and the market for them has saturated, in the sense that almost



everyone who needs them, has them. Then it is desire (“want”) not necessity (“need”) that generates market forces. Much product design today is driven by desire, and one of the things consumers desire is greater functionality. This shifts emphasis from structural materials, which, after decades (centuries, even) of development are evolving only slowly, toward materials that behave in novel ways. These are largely provided by non-structural materials: it is the electrical, optical, magnetic, and biological attributes that are important here. That is not to say that structural materials are dead – far from it: over 95% of all the

engineering materials that are produced are used primarily to carry mechanical loads. Research and development of these emphasize more efficient processing, greater control of quality, and more flexible manufacturing methods rather than a search for completely new materials. But while most cars – to take an example – are still made largely of steel, they also contain up to 30 small electric motors to position windows, seats, wipers and mirrors (magnetic and electrical materials), micro-processors for engine control and guidance systems (semi-conducting materials), toughened and non-reflective glass, liquid crystal and LED

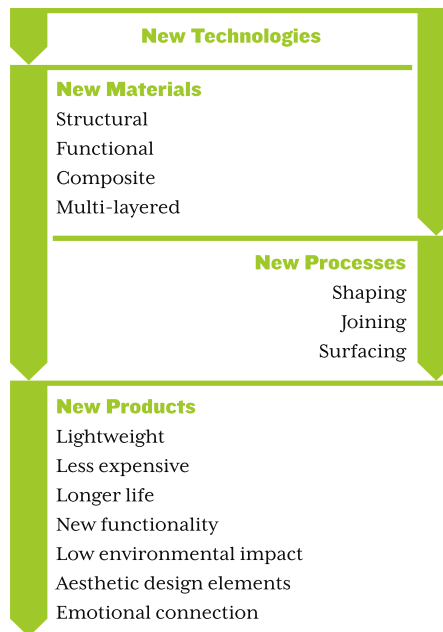
displays (optical materials), and flooring and paneling to insulate against heat and sound (thermal and acoustic materials). It is here that much current research and development is focused.

It is usual to suggest that designers respond to market needs, but sometimes it is the designer who creates the need. Revolutionary products take the market by surprise – few people felt the need for a Walkman, or a digital watch or a laser-ter before these appeared in the marketplace. Here the designer anticipated a need, and by providing a solution, created it. The inspiration behind these concepts arose not from the market, but from advances in science and technology – the development of high-field magnets, of quartz oscillators, of solid-state lasers – to which we now turn.

Most products that are intentionally designed start with an exploration of human behaviors to understand what people want and what people need and how products that we make will be part of their daily life. This discipline is sometimes called Human Factors or Design Research – under either title the goal is to take a human-centered approach to market and consumer research and really have a conversation with individuals about what to make and why.

Science and Technology

The least predictable of the driving forces for change is that of science itself (2.2). Despite periodic predictions¹ that science is “coming to an end,” it continues to expose new technologies



2.2 The Role of Science

Science reveals new technologies, from these technologies emerge new materials and processes. These, in turn, stimulate new opportunities for product design.

that enable innovation in materials and processes.

As already said, it is structural applications that, in terms of tonnage, overwhelmingly dominate the consumption of engineering materials. Cement and concrete, steels and light alloys, structural polymers and composites – all a focus for research in the last century – have reached a kind of technical maturity. What can new science and technology offer here? Better materials for lightweight structures and for structural use at high temperatures offer such great potential benefits that research to develop them continues strongly. The drive toward miniaturization, too, creates new mechanical and thermal problems – the small size frequently means that the support structure must be exceptionally thin and slender, requiring materials of exceptional stiffness and

1. See, for example, [Horgan \(1996\)](#).

strength, and that, while the power may be low, the power density is enormous, requiring new materials for thermal management. The acknowledged future importance of MEMS devices (micro electro-mechanical systems) creates even greater challenges: materials for micron-scale beams, bearings, gears, and chassis that must function properly at a scale in which the laws of mechanics operate in a different way (inertial forces become unimportant while surface forces become influential, for example).

materials are electro-active polymers, amorphous metals, new magnetic and super-conducting intermetallics and ceramics, metallic foams, and lattice materials made by micro-fabrication or three-dimensional weaving. Research on materials that mimic nature in subtler ways is stimulated by the deeper scientific understanding of cell biology, suggesting new approaches for developing bio-active and bio-passive surfaces that cells can recognize. Nanoscale assembly techniques allow the creation of two-dimensional devices that respond to the motion of a single electron or magnetic flux-quantum. If the 20th century is thought of as the era of bulk, three dimensional materials, the 21st century will be that of surfaces, mono-layers, even single molecules, and the new functionality that these allow.

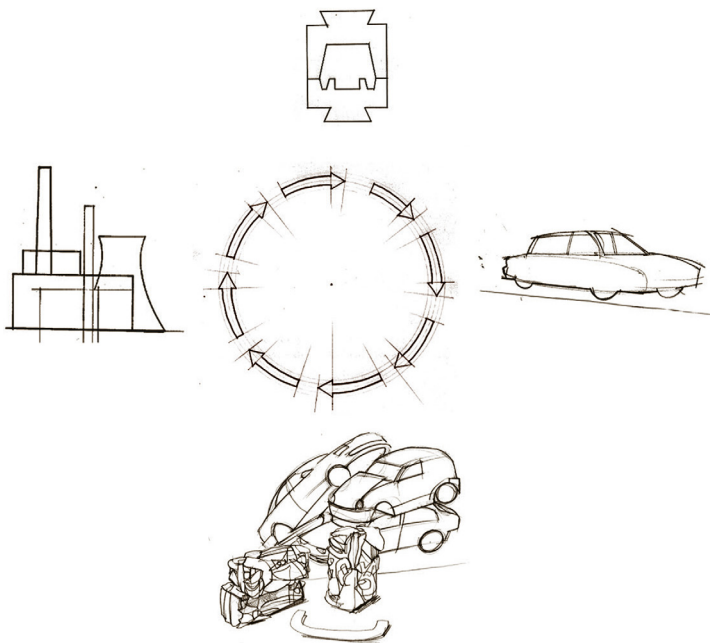
2.3 The Life of a Material

Ore and feedstock are mined and processed to give a material; this is manufactured into a product that is used and, at the end of its life, discarded or recycled. Energy and materials are consumed at each step, generating waste heat and solid, liquid, or gaseous emissions.

Above all, there is the drive to discover and develop novel functional materials. Some examples of established functional materials and their application were given in the last section. Many more are under development and will, in time, inspire innovative products. Examples of such emerging

Sustainability and the Environment

All human activity has some impact on the environment in which we live. The environment has some capacity to cope with this, so that a certain level of impact can be absorbed without lasting damage. But it is clear that current human activities frequently exceed this threshold, diminishing the quality of the world in which we now live and threatening the wellbeing of future generations. The position is dramatized by the following statement: at a global growth rate of 3% per year we will mine, process, and dispose of more stuff in the next 25 years than in the entire history of human



civilization. Design for the environment is generally interpreted as the effort to adjust the present product design process to correct known, measurable, environmental degradation; the time-scale of this thinking is 10 years or so, an average product's expected life. Concern for sustainability is the longer view: that of adaptation to a lifestyle that meets present needs without compromising the needs of future generations. The time-scale here is longer – perhaps 50 years into the future.

The real considerations in design for the environment are brought into focus by examining the material life-cycle, sketched in Figure 2.3. Ore and feedstock, most of them non-renewable, are processed to give materials; these are manufactured into products that are used and, at the end of their lives, discarded, a percentage perhaps entering a recycling loop, the rest committed to incineration or landfill. Energy is consumed at each point in this cycle, with an associated penalty of CO_2 and other emissions – heat, and gaseous, liquid and solid waste. The problem, crudely put, is that the sum of these undesired byproducts exceeds the capacity of the environment to absorb them. The visible injury is mostly local, and its origins can be traced and remedial action taken. Much environmental legislation aims at modest though continuous reductions in the damaging activity; regulation requiring a 20% reduction in – say – the average gasoline consumption of passenger cars is seen as posing a major challenge.

Sustainability requires solutions of a completely different kind. Even con-

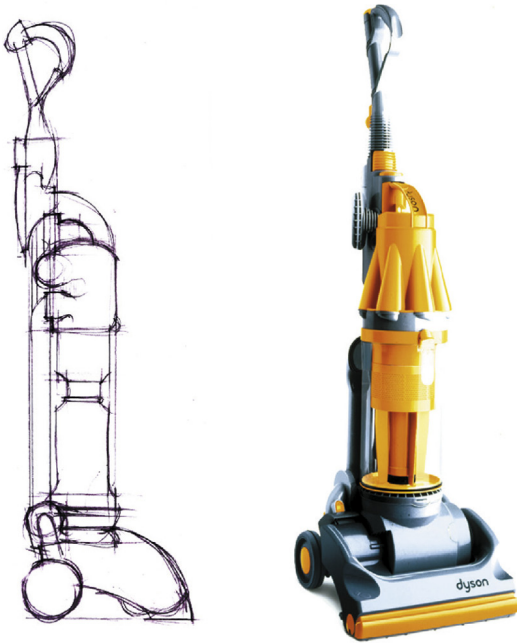
servative estimates of the adjustment needed to restore long-term equilibrium with the environment envisage a reduction in the flows of Figure 2.3 by a factor of 4; some say 10.² Population growth and the growth of the expectations of this population more than cancel any 20% savings that the developed nations may achieve. It looks like a tough problem, one requiring difficult adaptation, and one to which no answer will be found in this book. But it remains one of the drivers and ultimate boundary conditions of product design, to be retained as background to any creative thinking.

How, then, to respond to the nearer-term problem of reducing the impact of usage? One obvious way is to do more with less. Material reductions are made possible by recycling, by the use of renewable materials made from things that grow, by miniaturization, and by replacing goods by services. Energy reductions can be achieved by light weight design of transport systems, by the optimized thermal management of buildings, and by increased efficiency of energy conversion and utilization in industry. Probably the most effective measure of all is that of increasing product life: doubling life halves the impact of three out of the four stages of 2.3. And this refocuses the spotlight on industrial design – people don't discard possessions they love.

Economics and Investment Climate

Many designs have never reached the marketplace. Translating a design into a

2. The books by von Weizsäcker et al. (1997) and by Schmidt-Bleek (1997) make the case for massive reductions in the consumption of energy and materials, citing examples of ways in which these might be achieved.



2.4 From Concept to Product

The movement of an idea from concept to product requires demonstration of technical and economic viability, a receptive market and capital investment (Image courtesy of Dyson UK)

successful product (2.4) requires investment, and investment depends on confidence, on establishing economic viability. This relies in part on the design itself, but it also depends, importantly, on the nature of the market at which it is aimed, and the degree to which it can be protected from competition. The business case for a product seeks to establish its economic viability.

A product is economically viable if its value in the marketplace is greater than its cost by a sufficient margin to justify the investment required to make it; it is this that determines the potential revenue it can generate. Techniques of cost modeling allow estimates of the cost of production. Assessing value³ is more difficult, requiring market research to establish the consumers' perception of the product, the importance they attach to performance,

and the nature of the competition. Value depends on the market and industry at which the product is aimed: a titanium bicycle (to take an example) is attractive to mountain biking enthusiasts – to them, its value exceeds its cost; but it is not attractive to the average city shoppers, who perceive the cost to exceed the value.

Demonstrating economic viability is only one part of a credible business case. Establishing production requires investment, and this is forthcoming only if there is confidence in a significant level of value capture. The ability of the developers of the product to capture the value it offers relies on their ability to limit competition by retaining control of intellectual property and of key assets (people, trade secrets, licensing or partnership agreements). The investment required to commercialize a technically viable product will be forthcoming only if the technical, market, and business case assessments are all attractive. And finally there is the question of attitude to risk. Some industries are slow to adopt new technologies, whether viable or not: the nuclear industry, the civil engineering industry and, increasingly, the aerospace industry are among them. Others are not: manufacturers of sports equipment and of many consumer products eagerly seize upon new materials and processes and enthusiastically promote products made from them, accepting the risk that, being new and imperfectly characterized, they may fail prematurely.

This scenario has significant impact on material development. Developing, certifying, and commercializing a new structural material takes, typically, 15

3. See the article by [Clark et al. \(1997\)](#), listed under Further Reading, describing techniques of value analysis, utility, and technical cost modeling.

years, and it is not always obvious that it will be technically or economically viable when that point is reached. In the last century much of the development costs of structural materials were underwritten by governments through defense, space, and nuclear programs, willing to invest on a long time-scale – one that private industry is unwilling to accept. For functional materials, however, the time-scale for research and development can be shorter, and – partly because they can enable revolutionary products – their potential value can be higher, making them a more attractive investment. Thus the design process is influenced by the investment climate, judgments of expected profit and loss, sales volume, and ease of production; each of these relates directly to the development and commercialization of materials.

Aesthetics, Behavior and Industrial Design

Anesthetics numb the senses, suppress feeling; anesthesia is a lack of sensation. Aesthetics do the opposite: they arouse interest, stimulate, and appeal to the senses, particularly the sense of beauty. Synesthesia is the combination of senses: for some people this is a physical disorder, for designers it is inspiration. Aesthetic elements when surprisingly isolated or unexpected combined create new opportunities for design and the experiences that those designs enable. Aesthetics (like “inspiration”) is a difficult word, having too many shades of meaning to convey a sharp message, yet there

seems to be no other that quite captures the sensory attributes of materials and products. Designers manipulate these senses – and the reactions to each sense – to create a product’s personality.⁴

It has been argued in the past – and the argument is still sometimes used today – that a product designed to function properly will automatically have aesthetic appeal; that “form follows function.” This reasoning leads to the view that industrial design (defined as the exploration of both aesthetics and behavior and storytelling) as an active pursuit is unnecessary, since good technical design will produce it as a byproduct; industrial design, in this view, is mere packaging. And there is an opposing view: that products that are built around function alone have not been designed at all, but merely engineered. The reality, of course, is that both the technical and industrial design of a product influence its success and that of the company that makes it, and for very good reasons. Here are some.

Product Differentiation

Many products are now technically mature. Distinctions in technical performance are slight, and the prices of products with nearly the same performance are almost the same. As the market for a product saturates, sales can be stimulated by differentiation. This means creating product lines that are distinctive and have a personality that resonates with the tastes and aspirations of a particular user-group: an elegance that appeals to women, a rugged character that can survive an athlete’s use, a playful

4. A designer’s interaction with a material – or product – is probably better described as a synesthetic experience. Synesthesia is a psychological term that describes the physical experience of joined sensations. Many people say that they “see red” when angry, enjoy “sharp cheeses” with a glass of port, or like listening to “cool jazz”.

accessibility and tolerance of misuse that is appropriate for children. These details that have specific function and are intended to differentiate, also serve to create a design language and begin to elude to brand values (2.5).

Simple Interfaces

A product is safe, effective, and pleasing if the way it works can be read from its design: the use of size, proportion, configuration, and color to identify controls and what they do; the use of lights, sounds, displays, and graphics to present its current state. Product functionality has increased and while consumers want this they also want a small size and a simple, easy-to-understand interface. The physical size that is reserved for an “interface” has decreased and the space with which the designer is free to express

product use is limited. Good industrial design helps deal with this problem.

To solve more complicated interactions between people and products – an entire discipline (Interaction Design) has evolved, but – for sake of brevity – is not explored here.

Corporate and Brand Identity

The image carried by a corporation and its products is one of its most valuable assets; indeed, the primary asset of some companies is their brand. Creating and presenting a company’s brand and carrying it from one generation of products to the next is a function of industrial design that touches every aspect of the company: its products, its advertising, and even the architecture of its buildings. Empires, armies, religious orders, airlines, railways, corporations that make stuff – all of these use design to convey what they are, or how they would like to appear. Brand is about building emotional connections between the idea of a company and the products that company actually makes and sells. Materials and materiality are one way to build this connection between people and brand. It is important that the stories that companies tell and the brands they create have real and tangible design expressions and aren’t completely based on advertising and marketing.

Product Life

Products have a “design life” – a time span after which replacement is anticipated, but need not occur. In reality, a product comes to the end of its life when the market or user no longer wants it.

2.5 A Product Family

The use of the same materials and surface finishes creates a design language and brand elements that unite these four products (Image courtesy of Porsche Design GmbH).



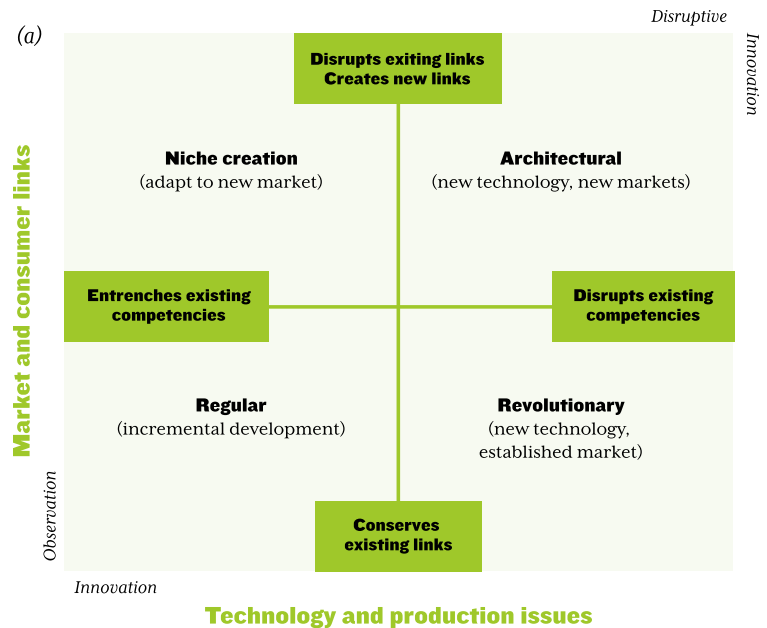
Cars have a design life of approximately 12 years, but classic cars survive far longer. A DC3 aircraft had a design life of 20 years – 60 years on they are still flying. The Eiffel Tower had a design life of only 2 years; more than a century later it stands as the symbol of Paris. In some ways, “classic” products are designs that are of such quality that they outlive their expected life – sometimes by many generations. Distinguished designs with elegant or imaginative use of materials survive because they are so endearing, symbolic, or evocative that they are treasured and preserved. Unremarkable designs with dull or inappropriate materials are, deliberately or accidentally, transitory; we discard them without a thought.

A Necessary Balance

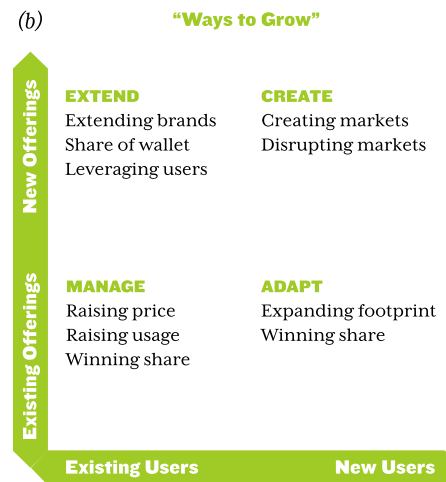
Products form part of the environment in which we live – in the home, in the workplace, on the street. Mass production now supplies products to a far larger market and in far larger numbers than in the earlier days of craft-based design, when few could afford them. In this sense mass production has enhanced the quality of life, but in others it has the capacity to diminish it. Our environment is enhanced by products that satisfy. By contrast if products create expectations that are not fulfilled, add nothing to (or even detract from) self-esteem or sense of place in society, or give no sense of satisfaction, then the quality of life has suffered.

Successful products depend on a balanced mix of technical and industrial design. This fact has been more

(a)



(b)



2.6(a) Transilience Map

The transilience map showing the four extreme types of innovation. The upper right is most disruptive but also has the greatest potential for profit.

2.6(b) Types of innovation

A 2×2 matrix for innovation (This matrix is taken from “Innovation, Growth and Getting to Where You Want to Go” by Jacoby and Rodriguez in *Design Management Review*, 2007).

readily accepted in architecture than in product design – architects⁵ speak of the three “ideals” of efficiency, economy, and elegance. There is an increasing awareness⁶ that similar ideals apply to product design. For these reasons

5. See, as an example, *Billington* (1985).

6. *Pye* (1997), particularly, makes this point.



2.7 Product Differentiation: Wristwatches

Above, watches from the era when they were expensive heirlooms. Below, extreme styling from Swatch (Image courtesy of Apple Publishers, London).



and others, industrial design is now as important an aspect of the total design process as any other. The examples that conclude this chapter illustrate these points further.

Types of Innovation

Products evolve through innovation; in more than one form, as suggested by the matrix of [Figure 2.6a](#), mysteriously known as a transilience map. The cell-headings don't explain themselves well, but we will stay with them because they are widely used by market analysts. Some innovation is incremental improvement of performance, reliability, or economy, built on established technical and production competence, targeting existing markets and customers (the normal process of product development). Niche creation exploits existing technology to capture new markets by adapting or developing it to increase its appeal to particular user-groups (re-designing car interiors to make them attractive to female drivers). Revolutionary innovations displace established technical and production methods, but allow a manufacturer to sell to their existing markets and customers (digital broadcasting replacing analog transmission, for example). Lastly architectural innovation involves new technology that disrupts both existing manufacturing competency and existing market and customer linkages (the much-cited example is that of the automobile replacing the horse-drawn carriage).

Design enterprises like IDEO, ARUP, or Porsche Design develop their own in-house strategies for innovation. The IDEO method (Jacoby and Rodriguez,

2007 shown in [Figure 2.6b](#)) is an example. It is based around a “Ways to grow” matrix with four sectors: “Manage,” “Extend,” “Adapt,” and “Create” that has much in common with [Figure 2](#). “Manage” and “Extend” correspond pretty closely to Regular and Niche innovation, “Adapt” to Revolutionary innovation and “Create” to Disruptive innovation relate to evolutionary change, “create” relates to revolutionary change.

Some Examples...

Product Differentiation – Wristwatches

Wristwatches have been commercially available since 1850, though for most of that time only the rich could afford them. As little as 40 years ago, a watch was a valuable and valued possession – a present for life given on a significant occasion ([2.7, top](#)). Once you had one watch, you didn't need another.

With increasing wealth after 1945, the market for watches broadened and saturated – meaning that practically everyone had one. The need to stimulate sales became a priority, and how better than to make watches an item of fashion, not just for the rich, but for everyone. Watches have become a commodity, mass-marketed, like clothes. As an example, a mail-order catalog published in 2001 (in which watches are only a tiny part) lists and illustrates 312 watches, most priced below \$50, some below \$10. All use digital technology and thus have a precision far higher than



2.8 Simple Interfaces: Mobile Phones

A few examples: from one of the first Nokia phones to the more recent BlackBerry, a leader in the smartphone category.

most people need – marketing on performance ceases to be relevant. If a watch is to sell for more than \$50 (and many, of course, do) it must appeal in some way to the consumer's sense of style, taste, and individuality.

If further demonstration of the recent dominance of industrial design in marketing is needed, consider the Swatch. Prior to 1975, Switzerland had a monopoly of the world manufacture of watches, sustained by the national brand-image of quality. The electronic watch, invented in the United States and then developed in Japan, was a catastrophe for the Swiss watch industry. By 1984, the number of watch-making houses, their output, and the workforce they employed, had all fallen to less than one-third of their peaks a few years earlier. Desperate for recovery, Swiss watchmakers collaborated to design a watch that was as accurate, better made, and thinner than those from the East Asian countries, and was competitively priced. More significantly, they devised the concept of the “collection,” a series of products, technically identical, but differing in color,

texture, pattern, and styling (2.7, bottom). Artists were commissioned to design one or a series; and each new design was given a name (“Calypso Beach,” “Lolita,” “Graffiti”). By 1989 the image was established and successful, not only in broadening the market, but encouraging individuals to buy not one watch, but two, ten..., a hundred, even. The brand has now launched some 1,000 designs of a single technical innovation.

Simple Interfaces – Mobile Phones

Mobile (cellular) phones typify recent and successful electronic innovations (2.8). Like the portable CD player, the Walkman, and even the personal computer, mobile phones now sell as much for their aesthetics as for their technical merit. Cellular communication systems require an established network of repeater stations; initial industry growth, around 1988, depended on a minimum network of these stations. The technology was new, taken up by “early adopters” – the relatively small group of consumers that love new technology and will buy it even before it works well



2.9 Corporate Identity: Bang & Olufsen

These images show a consistent and powerful corporate and product identity (Images courtesy of Bang & Olufsen, Denmark).

or is easy to use. Mobile phones of Some Examples... that era were brick-shaped, black, and heavy, with a “technical” image like that of military radiophones (2.8). Increasing the market required technical advances: lighter phones (meaning more efficient batteries and lower power-drain) and, with increasing concern about health risks, lower microwave intensity, and thus higher sensitivity. By 1995, coverage by repeater stations in developed countries was nearly universal and take-up of the technology had grown faster than anticipated. By 1999, the European and American markets were approaching initial saturation.

Most mobiles now have more organic forms and make extensive use of color and pattern, and come with snap-on covers to match clothes, mood, or occasion. Contemporary mobiles exploit the visual and tactile attributes of materials, to produce products that appeal to a wider range of social groups and to create shifting design trends that makes a one-year-old model appear out of date. Translucent

cases with dimly visible innards, pop-art or high-art décor like the “Mona Lisa,” and limited editions all are ways of stimulating markets. Perceived value has now supplemented technical value as a driver in design. Other recent innovations have followed the same patterns, with differing time-scales. The Walkman (launched 1970), the portable CD player (launched 1980), the computer mouse (launched 1984) have transmuted from functional, dull, and flat objects into objects that are translucent or brightly colored, sculptured, and emotional.

Corporate Identity – Bang & Olufsen

Anyone with the smallest interest in stereo and audio equipment can recognize a Bang & Olufsen (B&O) product even if they have never seen it before (2.9). In the late 1960s, this company set out to establish a recognizable corporate identity through the design of its products. Its radios, televisions, and phones were – and are now – made recognizable by high-tech shapes, sharp edges, flat surfaces,



careful choice of finish and neat, clean graphics. The combination of wood veneer, satin finished aluminum, and stainless steel combines to suggest quality, and attention to detail. Knobs, moving lids, and complex controls are eliminated, replaced by infrared sensors, and simplified remote controls. The designers have sought to combine the discrete with the remarkable.

Bang & Olufsen express its philosophy⁷ in the following way. “Design is nothing unless it is used to unite form and function... We have never tried to be the first to introduce new technology... Our aim is different: we want our products to make sense and to make you feel special in their company... We believe that such products are built by combining unrivaled technology with emotional appeal; products with personality that make people feel special and create emotional bonds... Most of our products come in a range of colors to present you with a choice, just as if you were buying a new sofa... Our colors don’t follow fashion, but they will match your furniture... Surface textures are another design element which some would regard as secondary, but which we care about deeply... We have but one rule: Bang & Olufsen products must create an immediate understanding

of their performance. We aim to surprise with unusual initiatives, to escape the sense of boredom of mass product development...”

Here is a company that sees perceived value, created by focused industrial design, as central to product recognition and appeal, and to corporate identity. Its continuing profitability and success suggest that it is right.

Types of Innovation – USB Keys

In the early days of digital information storage, the storage medium was punched tape. It was displaced in the 1960s by punched cards, and, quickly thereafter, by magnetic tape. Tape displaced vinyl and acetate as the recording medium for music and film, displaced in turn by the CD in the 1980s and the DVD in the 1990s. These are now overshadowed by digital downloads coupled with solid-state data storage, of which the most visible form is that of the USB key, which provides a nice example of product evolution through innovation.

Early USB keys were undistinguished black boxes with a capacity of 64 or 128 MB. They were purely functional, with no attempt at market differentiation. Not surprisingly the early innovation was characterized by the expansion of capacity first to 1 GB, then to 8 GB and

2.10 Types of Innovation: USB Keys

(a) Stainless steel from Cartier (Source: www.gizmodo.com). (b) Analog cassette tapes from Mixa (Source: www.makeamixa.com). (c) Swarovski crystal (Source: blog.getitnext.com). (d) Molded RVC from mimobot (Source: www.gizmodo.com). (e) Wood from oooms (Source: www.oooms.nl)

7. Bang & Olufsen (2002).



2.11 Material Evolution: the Camera

From metal to polymer to paper to metal-coated polymers, the evolution of materials is shown in these selected cameras.

beyond, and the incorporation of faster USB2 addressing. As supply grew and the market began to saturate, the natural progression was toward niche-creation (2.10a–d).

Material Evolution

The influences on product design discussed earlier – technology, the environment, the investment climate, and industrial design – result in an evolution in the use of materials for a given product or product class. Here are two examples – the camera and the hairdryer.

2.12 Kettles

(from left to right: cast iron, brass, stainless steel, polypropylene).

Kettles

The kettle is the oldest of household appliances and the one found in more

homes than any other – there is evidence (not entirely convincing) of a 4000-year-old kettle. Early kettles, heated directly over a fire, were of necessity made of materials that could conduct heat well and withstand exposure to an open flame: iron, copper, or bronze. Electric kettles, developed in the 1890s, had external heating elements to replace the flame, but were otherwise much like their predecessors. That changed with the introduction by the Swan company (1922) of a heating element sealed in a metal tube placed within the water chamber. The kettle body no longer had to conduct heat – indeed for safety and ease of use it was much better made of a thermal and electrical insulator. Today almost all are made of plastic, allowing economic manufacture with great freedom of form and color. Figure 2.12 shows examples of these kettles.

Cameras

The optics of the camera (Figure 2.11) are much older than the camera itself. Lenses capable of resolving the heavens (Galileo, 1600) or the microscopic (Hooke, 1665) predate the camera by centuries. The key ingredient, of course, was the ability to record the image (Joseph Nicéphore Niépce, 1814). Early cameras were made from wood, brass, leather,





and, of course, glass. They do have a certain style: that of the cabinet-maker, reflecting their craft-based manufacture. Bit by bit they became tools of art, business, and science and evolved to become more like scientific instruments, the emphasis more on functionality than on visual appeal. The materials chosen for these cameras were mostly metal – they were durable and put an emphasis on “engineered” quality. But as the market for the standard product started to saturate new variants appeared: the disposable camera (made of paper), the miniature spy camera (metalized polymers), and waterproof cameras (elastomers overmolded on a range of polymers) – differentiation through technical innovation is often coupled with changes in material. Technical development continues today: the zoom lens and digital imaging are examples. But this has gone hand-in-hand with differentiation of a different kind: cameras for children, cameras for under-water tourism, instant cameras, cameras to be worn as fashion accessories. [Figure 2.13](#) shows some examples. Here it is worth noting how products make evolutionary jumps, redefining their role, and capturing new markets. The jump from film-based photography to digital imaging is an example. The evolution of phones

from traditional landline connection to mobile technology is another. The jump from balance-wheel to quartz-oscillator time-keeping is a third. These are what are called “revolutionary” innovations, meaning that they frequently disrupt existing markets because the new technology is controlled by a different manufacturing sector than the old.

Hairdryers

Electric hairdryers first became widely available about 1945. Little has changed in the way that their function is achieved since then: an electric motor drives a fan

2.13 Camera

(from left to right: wood, metal, plastic, paper).

2.14 Material Evolution: the Hairdryer

From cast iron to pressed steel to injection molded polymers.



2.15 The First Baby Buggies

(a) *The Silver Cross Balmoral*. (b) *A folding param*. (c and d) *Sport buggies*.

(a)



(b)



(c)



(d)



which propels air through heating elements, whence it is directed by a nozzle onto the hair. Early hairdryers (2.14a) had a power of barely 100 watts. They were made from zinc die castings or pressed steel sheet, and they were bulky and heavy. Their engineering was dominated by the “metal mentality”: parts that could be easily cast, pressed, and machined were held together by numerous fasteners. Metals conduct both electricity and heat, so internal insula-

tion was necessary to prevent the user from getting electrocuted or burned. This, together with inefficient motors and fans, made for a bulky product. The only technical development since has been that of the centrifugal fan, allowing a slimmer design by putting the motor at the hub of the fan itself (2.14b).

The development of polymers led to hairdryers that at first used Bakelite, a phenolic resin (2.14c), then other polymer materials, for the casing and

handle. The early versions are plastic imitations of their metal counterparts; the Bakelite model has the same shape, the same number of parts but even more fasteners than the metal one. Polymers were at first attractive because of the freedom of decorative molding they allowed. Hairdryers began to lose some of their industrial form; they were aimed at a more fashion-conscious public. But these designs did not exploit the full advantages offered by polymers: brighter colors, more complex moldings which interlock, snap-fasteners for easy assembly and the like. There were some gains: the unit was lighter, and (because the thermal conductivity of polymers is low) it didn't get quite so hot. But if the fan stalled, the softening point of polymers was quickly exceeded; most old hairdryers that survive today from this era are badly distorted by heat. Nonetheless, smaller motors and better thermal design pushed the power up and the weight down, and allowed a reversion to the more efficient axial flow design (2.14d).

The changes in design described above derive largely from the introduction of new materials. The tiny motor of a modern hairdryer uses ceramic magnets and a ceramic frame to give a high power density. Sensors detect overheating and shut the unit down when necessary. The higher velocity of airflow allows a heater of high power density and reduces the need for insulation between the heating element and the casing. The casing is now designed in a way that exploits fully the attributes of polymers: it is molded in two parts, generally with

only one fastener. An adjustable nozzle can be removed by twisting – a snap fit, exploiting the high strength/modulus ratio of polymer. The design is now youthfully attractive, light, and extremely efficient. Any company left producing pressed metal hairdryers when a unit like this becomes available finds that its market has disappeared.

Hairdryers have, for some years now, converged technically. Increased market share relies on creating demand among new social groups (children, athletes, travelers...) and in new models that differ in their visual, tactile attributes, and other associations: Snoopy hair dryers for children; miniature sports/travel dryers weighing much less than expected. In each case, materials and design are used to enable technological advances and capture the consumer's attention, and increase market share.

Materials and Society

Baby Buggies

The British company Silver Cross has been making baby buggies – well, no, perambulators – since 1877. These were coach-built carriages, Bentleys for Babies, intended for families who could afford a nanny to wheel the infant in the park rather than do it themselves. Their models had names like Fleur de Lis (symbol of Bourbon Kings of France) and Silver Cross Balmoral (one of the homes of the British Queen). Observe the example at the top of Figure 2.15a: large overlapping wheels attached to enormous leaf-springs linked with leather

straps to a wood-framed, hand-built carriage with hood struts and hand grip that come straight from the Hansom cab of the days of Sherlock Holmes.

The original company survived the austerity following World War II but went into receivership in 2002. Families without nannies need affordable baby-transport that can also carry purchases and fold to go into the back of the car or in the hallway of a small house. The evolved product (2.15b) derives more from the design of supermarket trolleys than of Hansom cabs: tiny wheels, tubular steel frame, wire mesh tray.

In the mid-1980s the perception of shared parenthood penetrated the world of the pram makers. Shopping with babies was no longer the exclusive privilege of the nanny or mother. Add to that the freedom that rising income had provided for vacations in exciting places and participation in exciting sports. The need, then, was for a carriage that could appeal to the male as much – or more – as to the female. Three current models that aim to fill this need are shown in the lower part of the figure: the Baby Enterprise All Terrain push chair, the Slalom Pro Baby Buggy, and the Jogger. The suggestion of robust outdoor activities only starts with the name. The rugged construction, nobly tires, cable brakes, quick release wheels have their origins in mountain bike design; the lightweight frame and tough webbing derives from that of Himalayan back packing gear; the baby harness from Formula 1 racing. All have been “field tested to meet the most demanding conditions.” The metaphors are effective.

It is models like these that now dominate the market.

Implicit in this are the materials that have been used to create the character of each product. The silk-lined, lacquered, wood-framed body of the Balmoral, with chromed brass fittings and the use of leather and canvas evoke tradition and individual craftsmanship. The tubular steel frame, welded mesh, and solid rubber tires of the folding chair are the materials of simple, strong construction. The wire-spoke wheels, aluminum and CFRP frame, and tough nylon webbing of the sport buggies are the stuff of outdoor, go-anywhere equipment, suggesting freedom, health, and exercise.

Conclusions

Today industrial design is integrated into the design process of most new products, and in a world of global competition, it makes good business sense to do so. In some products – sunglasses, skis, coffee makers – the influence of the industrial designer is more obviously central than in others – light bulbs, machine tools, jet engines – but even here it can be found. Next time you step off a plane, glance for a moment at the discretely noticeable Pratt and Whitney or Rolls Royce logo on the engine cowling – its styling is no accident. In short: technical and industrial design are the essential, complementary, parts of the design of *anything*.

This book seeks to explore the role that materials can play in balancing technical and industrial design and the selection of materials in product design itself.

Further Reading

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Ashby, M.F. (2013) "Materials and the Environment," Butterworth-Heinemann, Oxford, UK. ISBN 978-0-12-385971-6. (A teaching text that provides the resources – background, methods, data – to enable environmental issues to be introduced into the Materials courses.)

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Billington, D.P. (1985) "The Tower and the Bridge, New Art of Structural Engineering," Princeton University Press, Princeton, NJ, ASM. ISBN 0-69102393-x. (Professor Billington, a civil engineer, argues that great structures – the Brooklyn Bridge, the skyscrapers of Chicago, the concrete roof-shells of Pier Luigi Nervi – not only overcome technical challenges but also achieve the status of art. Much is biographical – the achievements of individual structural architects – but the commentary in between is forceful and enlightening.)

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Clark, J.P., Roth, R. and Field, F.R. (1997) "Techno-economic Issues in Materials Science," p. 255. Materials Selection and Design, ASM Handbook," Vol 20, ASM International, Materials Park, Ohio, USA ISBN 0-87170-386-6. (The authors explore methods of cost/value analysis and environmental issues in material selection.)

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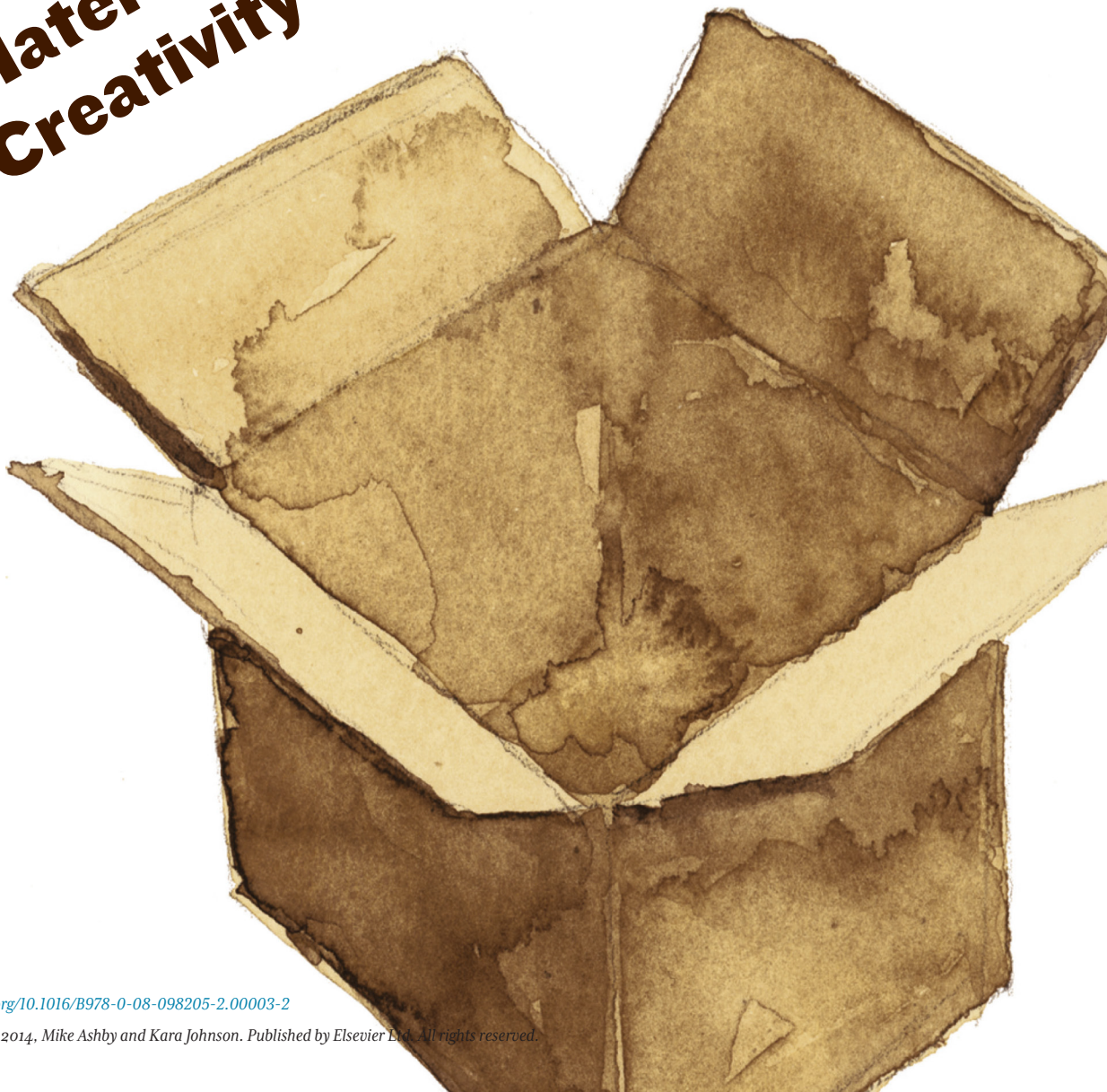
Schmidt-Bleek, F. (1997) "How Much Environment Does the Human Being Need – Factor 10 – The Measure for an Ecological Economy," Deutscher Taschenbuchverlag, Munich, Germany. (The author

argues that true sustainability requires a reduction in energy and resource consumption by the developed nations by a factor of 10.)

Von Weizsäcker, E., Lovins, A.B. and Lovins, L.H. (1997) "Factor Four," Earthscan Publications, London, UK. ISBN 1-85383-407-6. (The first publication to take the disturbing, but defensible, point of view that sustainability requires massive changes in human behavior and consumption.)

Chapter 3

Materiality, Design, and Creativity



In Italian there is one inclusive word for design and engineering – “la progettazione”¹; a designer or an engineer is “il progettista.” Translated literally, “il progetto” is the plan. In English, too, the word “design” is defined as “the plan,” with an even wider spectrum of meanings: design with regard to fashion – like hats; or with regard to aerodynamics and fluids – like that of turbine blades; or even with regard to states of mind.² Such breadth of meaning creates opportunities for confusion. To avoid this, we will speak of *technical design*, *industrial design*, and *product design*, using these words with the following sense.

It is also important to note, in the following discussion of design and creativity, we are always considering the application of each concept in our world of materiality and making. This is not intended to be exhaustive review of nor a recommendation for the right or best design methodology or creativity technique. We have presented a wide range that can inspire or guide the many types of readers that this book attracts.

Technical (or engineering) design includes the aspects of design that bear on the proper technical functioning of the product: its mechanical and thermal performance, cost, and durability. We shall call these, collectively, the technical attributes of the product – attributes that describe how it works and how it is made. Industrial design includes the aspects of design that bear on the satisfaction afforded by the product: the

visual and tactile attributes, associations and perceptions, historical antecedents – attributes that describe its personality or character. Product design, in the sense we use it here, means the synthesis of technical and industrial design to create successful products.

There is a risk in drawing these distinctions that technical and industrial design will be seen as separate, unconnected activities. A more balanced view is that they form a continuum, that they are simply parts of the overall design process. But while technical design utilizes well-established methods and sophisticated computer-based tools, industrial design cannot so easily be made systematic or quantitative. Unlike the technical attributes, which are absolute and precisely specified, many attributes of industrial design depend on culture and on time: the Japanese ideal of

1. Adapted from Manzini's (1989) remarkable book “Materials of Invention.”

2. “I don't design clothes, I design dreams” – Ralph Lauren, NY Times, 19 April 1986.

beauty differs from that of the European; and what is beautiful to one generation can appear ugly to the next. Scientific and technical language and thinking work well when ideas can be expressed explicitly and precisely, but these break down when the ideas are imprecise or involve subjective appreciation or taste; then, other ways of thinking are needed.

Ways of Thinking

Technical design relies on deductive reasoning – thinking based on logic and analysis. Deductive reasoning, applied to the selection of materials, is described more fully in Chapter 7. It lends itself to formulation as a set of steps, often involving mathematical analysis. Industrial design, by contrast, relies on inductive reasoning – synthesis, drawing on previous experience. Inductive methods for selecting materials, also explored in Chapter 7, use perception and visualization. These we need to explore more fully since they are central to the discussion that follows.

3.1 Differing perceptions

(Image courtesy Harley Davidson USA and Piaggio Corporation.)



Observation and Perception

Imagine yourself to be standing in a motorcycle tradeshow behind two men

who are looking at a Harley Davidson (3.1). The Harley has technical attributes, listed in its specification: weight, number of cylinders, power, maximum speed, the material of which the frame is made – these and many other attributes can be precisely defined and accurately measured. The Harley also has aesthetic attributes – it is black, metallic, and loud. The two men see the same motorcycle but they perceive it in different ways. In the mind of one is an ideal image of a smooth, yellow, urban scooter, without visible mechanical parts, clean lines, and trendy styling; he perceives the Harley as heavy, extravagant, and dangerous. The ideal in the mind of the other is an image of an open road, a black leather bodysuit, a helmet with darkened Visor, twin-exhausts; he perceives the Harley as powerful, authoritative, an expression of freedom.

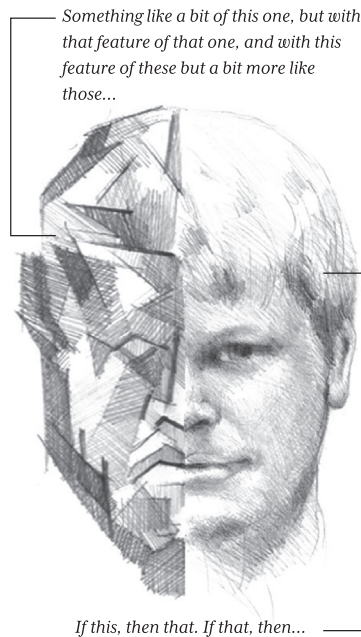
Perception is the result of interpreting what is observed. Two observers of the same product will perceive it in different ways, ways that derive from their reaction to the physical object they see and the accumulated mental images and experiences they carry with them. Both observation and perception contribute to creativity in design, and here it is necessary that we sharpen the definition of four terms we will use to describe, in increasing order of abstraction, the attributes of products – particularly those relating to industrial design and the personality of a product.

- *Aesthetic attributes* are those that relate directly to the senses: sight, touch, taste, smell, hearing; those of sight

include the form, color, and texture of a material or product.

- *Attributes of association* are those that make a connection to a time, place, event, person, or culture – thus a jeep has military associations, gold has associations of wealth, the color black of death, the color red of weddings.
- *Perceived attributes* describe a reaction to a material or product – that it is sophisticated, or modern, or humorous, for instance; these reactions are a sum of what you initially perceive and are heavily influenced by context and experience.
- *Emotional attributes* describe how a material or product makes you feel – happy, sad, threatened perhaps – “emotional ergonomics,” in the words of Richard Seymour of SeymourPowell, London.

To these we add the idea of style, based on design history. Styles have names: Art Nouveau, Art Deco, Modernist, Post-Modern, etc. Each is shorthand, so to speak, for a particular grouping of aesthetic, perceived, and emotional attributes and associations – one about which there is general agreement. Design styles, sometimes, are linked to certain materials, but it cannot be said that a material has a style, only that it acquires one when it becomes part of a product. Examples developed later in this and the next chapter will make these distinctions clearer.



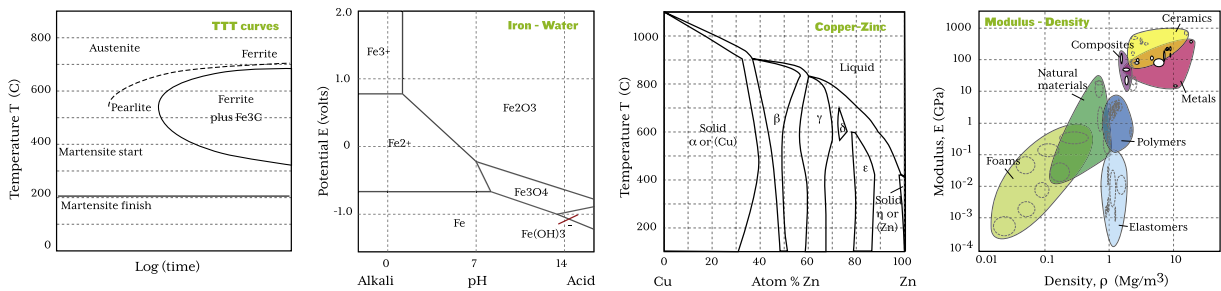
3.2 Left Brain, Right Brain

Thinking from the left or right – the first seeking solutions by logic and analysis, the second seeking solutions by synthesizing elements from recalled or imagined images or analogies.

Verbal-Mathematical and Visual Thinking

Writers such as McKim,³ discussing ways in which the human brain manipulates information in order to reason, distinguish two rather different processes (3.2). The first, the domain of the left-hemisphere of the brain, utilizes verbal reasoning and mathematical procedures. It moves from the known to the unknown by analysis – an essentially linear, sequential path. The second, the domain of the right-hemisphere, utilizes images – both remembered and imagined. It creates the unknown from the known by synthesis – by dissecting, recombining, permuting, and morphing ideas and images. The first way of thinking, the verbal-mathematical, is based on learned rules of grammar and logic. The second way of thinking, the

3. McKim's book "Experiences in Visual Thinking" (1980) explains better than most of the ways in which images enter the creative thought process.



3.3 Images from Material Science

Some of the ways visual images occur in material science (left to right): Electron micrographs; Optical micrographs; Phase diagrams; Deformation mechanism maps; Material property charts.

visual, makes greater use of the imagination; it is less structured but allows greater conceptual jumps through free association.

Think for a moment about the following example of the way you store visual information. You probably know and recognize several hundred people, perhaps many more. Could you, if asked to draw a recognizable picture of any one of them, do so? Most people can't; many can't even conjure up a picture of the face in their "mind's eye" (their imagination). This suggests that the visual image is stored only in a very crude way. Yet if you unexpectedly encountered a person that you know in – say – Los Angeles International Airport, you would instantly distinguish them from the thousands of other people there. Recognition of a face or a place requires a detailed comparison of a visual image with an image stored in the mind, seeking a match of a very subtle kind – and the average person can store enough information to recognize and distinguish not one, but hundreds of these. The way the mind stores images is not well understood but it is clear that its image database is very large and, when triggered, capable of very rapid access and great precision.

Creativity in design (both technical and industrial) involves the free association and combination of images to achieve a desired set of attributes. The images may be visual – observed objects, photographs, sketches, and drawings – or mental – stored in the memory and imagination of the designer.

Visual Thinking in Material Science

The word "science" immediately suggests deductive reasoning – analysis. But creative scientists from Leonardo da Vinci and Newton to Einstein and Crick/Watson testify that their moments of great insights arose as much from synthesis – visual thinking – as analysis. Material science, particularly, makes use of images for communication and as a way of thinking (3.3). Venn diagrams and flowcharts illustrate relationships and procedures; bar charts and graphs show magnitudes and numerical trends. Schematics display molecular structures, show how mechanisms work or how equipment functions.

Information can be more densely packed in diagrams and images that show relationships. Phase diagrams relate the regimes of stability of competing alloys. Micrographs reveal structural similarities between differing materials,

suggesting, perhaps, that a heat treatment used for one might be effective for another. Deformation mechanism maps relate the regimes of dominance of competing deformation mechanisms. Material property charts⁴ relate a population of materials in material property space, a space with many dimensions. Each of these captures a vast amount of information and compresses it into a single image, revealing patterns in the data that words and equations do not. It is here that they become a tool not only for communication, but also for reasoning.

The power of the visual image lies in the ease with which it can be manipulated by the mind and its ability to trigger creative thought. A picture of a car tail light made of acrylic, taken to show its transparency and ability to be colored, reveals much more: that it can be molded

to a complex shape, that it can withstand water and oil, and that it is robust enough to cope unprotected with use in the street. Diagrams showing relationships, particularly, have the power to trigger new ideas – examples in Chapter 4 will show how plotting material information can suggest novel material composites and combinations. Without the visual image, these ideas do not so easily suggest themselves. Visual communication and reasoning, then, have a long-established place in the world of material science. But how are they used in design? To answer that we must examine the design process itself.

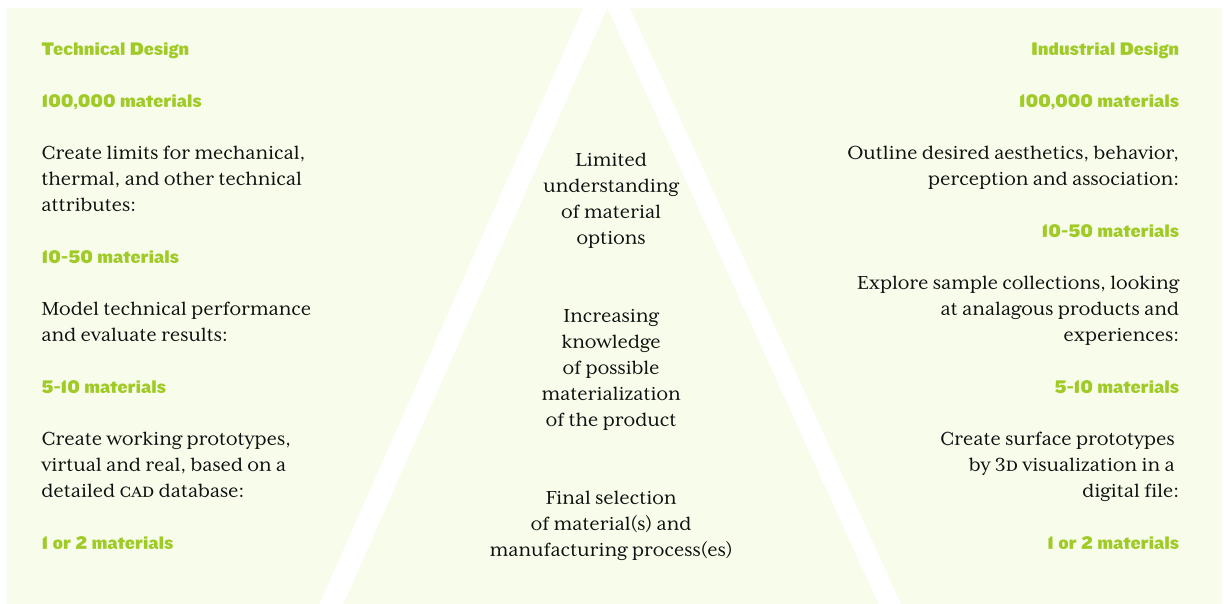
4. These charts, used extensively in the book, are introduced in Chapter 4.

3.4 Materials in the Design Process

The design of a product proceeds from an identification and clarification of the task through concept, development, and detailed design to a final product specification. Initially all materials (of which there are perhaps 100,000 in all) are candidates. Technical constraints (center) and constraints of industrial design (right) narrow the choice, leading to a small number that can be explored in detail.

The Design Process

First, a word about types of design. Original design starts from a genuinely new idea or working principle: the lamp



bulb, the telephone, the ball-point pen, the compact disk the mobile phone. More usually, design is adaptive, taking an existing concept and seeking an incremental advance in performance through refinement.

The starting point of a design is a market need or a new idea; the endpoint is the full specification of a product that fills the need or embodies the idea (3.4). It is essential to define the need precisely, that is, to formulate a need statement or design brief, listing product requirements, an expected environment of use, and possible consumers. Writers on design emphasize that the statement should be solution-neutral (that is, it should not imply how the task will be done) to avoid narrow thinking limited by pre-conceptions.

Between the design brief and the final product specification there are many steps. One way of modeling this design process is shown in the left-hand column of 3.4. Design, in this view, has three broad stages: conceptual design, development, and detailed design.⁵ The concept presents the way the product will meet the need, the working principle. Here the designer considers the widest possible range of ideas, both technical and aesthetic. The choice of concept has implications for the overall configuration of the design, but leaves decisions about material and form largely unanswered.

The next stage, development, takes each promising concept and develops it, analyzes its operation, and explores alternative choices of material and process that will allow safe operation

in the anticipated ranges of loads, temperatures, and environments. In parallel with this, alternative forms, colors, and textures are explored, seeking, in ways described in Chapter 6, materials and processes capable of creating them.

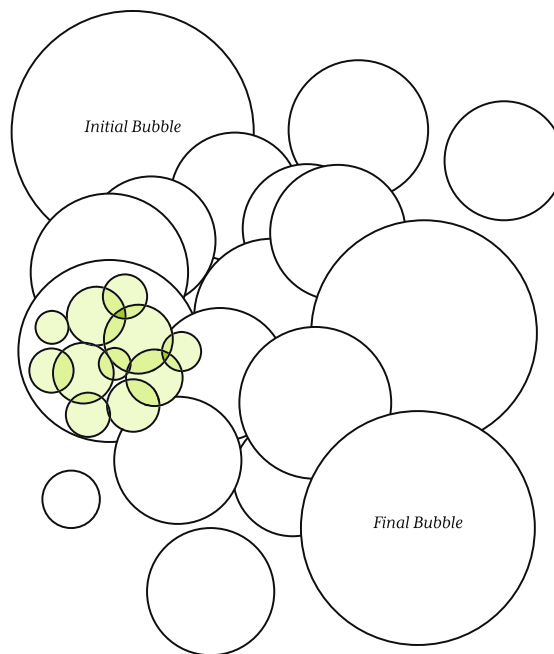
Development ends with a feasible design that is then passed on for detailing. Here specifications for each component are drawn up; critical components are subjected to precise mechanical or thermal analysis; optimization methods are applied to components and groups of components to maximize performance, and costs are analyzed. Three-dimensional surface models are used to develop form, and a final choice of geometry, material, manufacturing process, and surface is made. The output of this stage is a detailed product specification.

In this way of thinking, materials information is required at each stage of the design (3.4). The nature of the information needed in the early stages differs greatly in its level of precision and breadth from that needed later on. In conceptual design, the designer requires generic information – broad character sketches – for the widest possible range of materials. All options are open: a polymer may be the best choice for one concept, a metal for another, even though the required function is identical. The need, at this stage, is not for precision; it is for breadth and ease of access: how can the vast range of materials be presented to give the designer the greatest freedom in considering alternatives?

5. Here we are using the words of a respected design text (Pahl and Beitz, 1997); many others follow this influential book on technical design.

The next step of development requires information for a subset of these materials, but at a higher level of precision and detail. Technical attributes are found in more specialized handbooks and software which deal with a single class of materials and property – corrosion resistance of metals for instance – and allow choice at a level of detail not possible from the broader compilations which include all materials. The material attributes relevant to industrial design are assembled in a different way – ideas gleaned from other designers and products, the study of material collections, the assembly of mood boards, the use of creativity aids, sketching, and model building – we return to all of these in a moment.

The final stage of detailed design requires a still higher level of precision and detail, but for only one or a very few materials – information best found by contacting the material supplier. A given grade of a material (polypropylene, for instance) has a range of properties that derive from differences in the way different suppliers make it. And sometimes even this is not good enough. If the component is a critical one (meaning that its failure could, in some sense or another, be disastrous) then it may be prudent to conduct in-house tests to measure the critical properties, using a sample of the material that will be used to make the product itself. The final step is to make and test full-scale prototypes to ensure that the design meets both the technical and aesthetic expectations of the customer.



The materials input into design does not end with the establishment of a product specification and final production. Products fail in service, and failures contain information. It is an imprudent manufacturer who does not collect and analyze data on failures. Often this points to the misuse of a material, one which re-design or re-selection can eliminate.

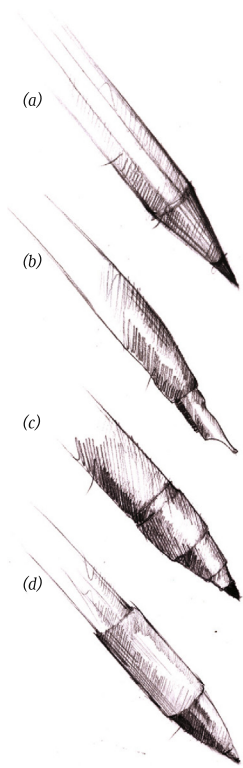
There is much to be said for this structured model of design. Its formality appeals to technical designers, trained in systematic methods for tackling problems of stress analysis or heat flow. But the degree of interdependence in design far exceeds that in stress analysis, so that design requires additional skills, more nearly like those of the experienced lawyer or politician – practiced in assembling and rearranging facts and in judging similarities,

3.5 Bubbles in the Design Process

An analogy for the design process. Adapted from Wallace (1991), in "Research in Design Thinking" a conference at the Technical University of Delft in 1991.

differences, probabilities, and implications. For design – and particularly for the role of materials in design – this model is perhaps too structured. It does not allow for the variety of paths and influences that lie between the market need and the product specification.

Ken Wallace, translator of the concept/development/detail design model from its original German, suggests another analogy – that of bubbles (3.5). Here each bubble represents a step in the design process or the output of such a step. There is no linear path from the initial “design brief” to the final “product specification”; instead, many paths link the thousands of bubbles that lie between them. It is important to get into the initial bubble – to confront the problem. But there is no identified path from that bubble to the final bubble and it is always possible that other bubbles will have significant influence. The bubble model is more representative of a random and unstructured design process. The most efficient designers can immerse themselves in the bubbles and have the appropriate resources to answer any challenges that may arise. Getting caught in one bubble – the weakness of the specialist – is fatal. Progress requires the ability to step back, seeing the bubbles as pattern as well as sources of detailed information, exercising control of the pattern and only unpacking the detail when it is needed. This is closer to our view of material selection as it relates to the design process and is expanded in Chapter 7 when we detail methods of selection.



3.6 Concepts for Writing

Sketches for four concepts for writing instruments: (a) Transfer of solid pigment by wear; (b) Marking by flow of liquid ink from a nib; (c) Marking by transfer from a porous felt or nylon; and (d) Transfer of oil-based ink via a rolling ball.

The Design of Pens – an Example

To illustrate these ideas, consider the design of pens. Pens are objects both of utility and of desire. It is possible to buy, for \$2, a pen that writes perfectly well; yet it is also possible to market with success one that costs more than \$2000. Pens exemplify products that combine technical and aesthetic aspects in a particularly effective way. Here we look briefly at their design.

The Original Concept

Ever since man devised a written language, a need existed for making accurate, durable marks on flat surfaces. Marks can be made by scratching or carving, but this is slow; the real need is for a compact instrument for marking quickly. Marking with pigments is the answer.

Figure 3.6 shows four concepts for making marks with pigments. In the concept at (a), marks are made by frictional transfer of solid pigments such as charcoal, graphite, or crayon (colored pigment in a wax or chalk base). In the concept at (b) a water-based pigment or ink is caused to flow onto the surface from a nib – a cut goose-quill, or a steel or gold equivalent – using surface tension to hold the ink in the nib and duct it to its tip. The concept at (c) also relies on surface tension; it uses a porous felt or nylon tip to suck up pigment from a reservoir where it is deposited on any surface that it touches. The final concept, shown at (d), rolls an oil-based pigment onto the surface with a ball, relying on the viscosity and the good wetting of the oil to transfer it to the ball.



3.7 Development of a Fountain Pen

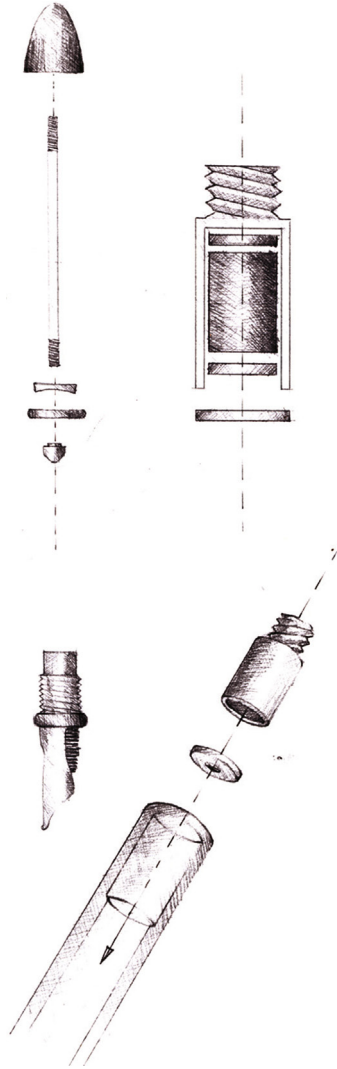
Development of a fountain pen, showing working principles and layout.

All of these could acquire their pigment by dipping in a well of ink or powdered pigment. But to be practical today, a pen must be capable of writing continuously for hours without recharging, and it must tolerate changes in temperature and (modest) changes in pressure without exuding ink where it is not wanted.

Iteration and Development

Figure 3.7 shows a development of a concept (b): it is a reservoir-fed ink pen. The diagram is largely self-evident.

The reservoir is filled by pumping a piston (which works like the piston in



3.8 Detail of a Fountain Pen

Detailed design: materials, processes, and dimensions are specified for each component.

a bicycle pump) attached to the tail of the pen. After filling, the tail is “parked” by screwing it down onto the pen body. Ink reaches the nib by capillary action through channels cut in the plug that through slots into its underside (not shown).

Design Details

To make the pen, much more must be specified. Figure 3.8 shows part of

the information developed during the detailed design stage: the analysis of stresses where necessary, optimization of weight and balance, precise dimensioning, costing and, of course, the choice of materials.

The invention of ebonite (1841) – heavily vulcanized rubber – coincided with the invention of the fountain pen, and proved a near-ideal material for its body, still occasionally used today. It can be machined, molded, and polished, and its rich black color makes it a sophisticated setting for gold and silver ornamentation. Its drawback is that colors other than black are difficult to achieve. New entrants in the now-competitive market (1880 onwards) switched to celluloid (a compound of nitrocellulose and camphor) because it is easily dyed, flexible, and tough, and allows special effects simulating ivory, mother of pearl, and other finishes. Bakelite (1910) proved too brittle for making pens, so it was not until after 1950 that much changed. But since then, synthetic thermoplastics that can be dyed, patterned, and molded quickly – notably acrylic – have dominated pen design. Special editions with metal bodies (stainless steel, titanium, silver) are all possible, but even these have polymeric inserts.

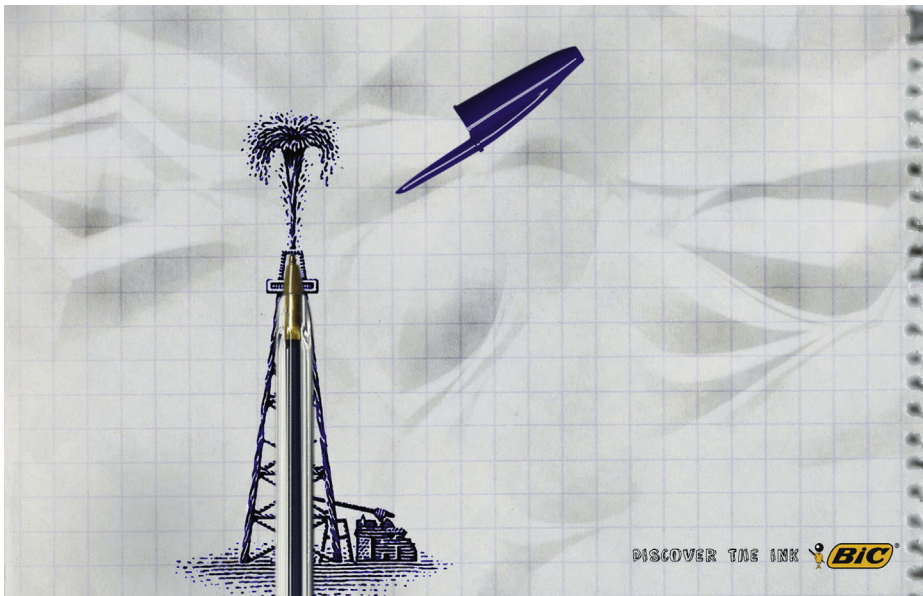
The dominance of gold for nibs arose because early inks were acidic and attacked most other metals. But gold, even when alloyed, is relatively soft, and wears when rubbed on paper, which contains abrasive ceramic fillers. This led to the inclusion of granules of osmium or iridium – both much harder than gold – into the tip, and this practice continues

today. The development of neutral inks now allows the use of other materials, notably steel, alloyed or coated to prevent rusting.

Why pay \$2000 for a pen when you can buy one that works very well for \$2 – well, \$5? (This book was written with a \$5 pen.) The history of writing carries many strings of associations. Here are a few. Writing > reading > love of books (“a home without books is like a house without windows”). Writing > learning > wisdom, leadership (“knowledge is power”). Writing > creativity > artistic acclaim (“a man of letters”). Writing > political persuasion > political eminence (“the pen is mightier than the sword”). Writing > books and libraries > personal wealth (public libraries are a comparatively recent innovation). Writing > letters > friendship, love (“letters – the elixir of love!”).

Here we have an unusually rich brew. The linked word-strings tap into the aspirations of large and diverse groups of people. For those to whom the links are apparent, a pen that discretely suggests the individuality of the owner is worth a lot more than \$5. Pen manufacturers have used this reasoning (or their own version of it) to great effect. The pen as an intellectual statement, or as an indicator of wealth, or good taste, or individuality, or youth, or fun: these are deliberate attempts to attract consumers through the personality of the product.

And now we see a sort of method at work, involving the following chain of reasoning. The product has a function. Here: writing. What associations does that function carry? Here: creativity,



3.9 Advertising the Bic Pen

The advertising message is clear, and builds on the materiality of the pen itself and what the Bic logo means to people. (Source: www.adsoftheworld.com)

artistry, refinement, power, riches, sophistication. Which of these associations are seen as desirable attributes of an individual? Here: intellectual refinement, artistic achievement, sophisticated taste, leadership, wealth. What features – visual prompts, stylistic references – can be applied to the product to suggest one or another of these associations? Expensive materials, discretely noticeable silver, gold, or enamel ornamentation, classical form, graphics and color suggesting recognizable artistic movements, form and surface hinting at youthful vigor and vision. The same reasoning motivates advertising: the pen seen in the hand of the Pope or of a well-known actor, the pen in opulent surroundings next to bejeweled objects, the pen lying on a sheet of classical music. Figures 3.9 and 3.10 look at one example, the Bic pen, in more detail.

Product design in the 21st century must deliver a blend of function, use, and personality. The first requires good technical design – products must work properly. The second is a question of human factors or ergonomics – the matching of the product to the physical and mental abilities of the user. The last is a compound of both of these and something more – the delight afforded by good industrial design. It is the role of designers to create this many-sided personality. But where do they get their ideas?

Sources of Inspiration

Newspaper reporters, it is said, never relax. Half their mind is always alert to

3.10 A Pen and its Utility

Ladislav Biro, a Hungarian, patented the ball-point pen in 1935. But he ran out of money and sold the idea to Marcel Bich who, in 1950, launched the BIC pen. Though cheap, thought has gone into the shape, color, and texture. The clear shell allows you to see how much ink is left, its hexagon shape keeps the pen from rolling off your desk, and the color of the caps matches that of the ink. The Bic Pen Company now sells over 3 million pens per day.



the possibility that a news story might be about to break just round the corner. Relax and they'll miss it – worse, another reporter may get it first. Conversations with designers reveal a similar syn-

drome: they are always alert to the possibilities offered by a shape, a texture, a material, a surface, an image that might be adapted in an innovative design. It is a characteristic not confined to product

3.11 Museums of Design and Country Applied Art

Design museums are a rich source of inspiration for designers.

Country	Design museums
Australia	The Powerhouse Museum, Sydney
Britain	The Design Museum, London The Victoria and Albert Museum, London The Science Museum, London
Czechoslovakia	Musée National des Techniques, Prague
Denmark	The Danish Museum of Decorative Art, Copenhagen Danish Design Centre, Copenhagen
France	Musée Nationale des Techniques, Paris Musée des Arts Décoratifs, Paris Musée National d'Art Modern, Paris. The Musée d'Orsay, Paris Fondation National d'Art Contemporain, Paris
Germany	Das Deutsche Museum, München Vitra Design Museum, Weil am Rhein
Holland	The Stedljk Museeum, Amsterdam The Booymans van Beumijen Museeum, Rotterdam
Italy	Sandretto's Plastics Museum, Pont Canavese
Sweden	The Form Design Center, Malmo
Switzerland	Design Collection, Museum für Gestaltung, Zurich
USA	The Smithsonian Museum, Washington DC Museum of Modern Art (moma), New York The National Academy of Design, New York Cooper-Hewitt, New York

designers: fashion designers and architects also use what they have observed and their ability to manipulate it as a creative tool.

Industrial designers and engineers, like fashion designers and architects, describe their work as “creative,” implying that their best ideas are self-generated, the result of a sort of inspiration. But even inspiration has its sources and methods.⁶ Discussions with designers suggest several and emphasize the central role of materials and processes in each. Here are some.

Design Magazines, Annual Reviews, Museum Exhibitions, and Tradeshows

Design magazines⁷ and annual reviews⁸ illustrate innovative products, attaching a brief description listing designer and – sometimes – materials. Design yearbooks⁹ do much the same, but devote more space to the design history and antecedents, to motivation, and to descriptions of features, often augmented by interviews with the designers themselves. Browsing through these

can provide inspiration, but the largely unstructured nature of the information that they contain makes their efficient use difficult. Most designers also seek ideas from a wider range of sources encompassing fashion, architecture, and design publications such as *Vogue*, *Domus*, and *Wallpaper*. Design exhibitions¹⁰ expose the viewer to rich sources of ideas drawn from diverse product sectors, often suggesting the use of materials in a product to achieve a particular feel, texture, color, or association. Museums of design and applied art (3, 11) record design history and innovation, combining permanent displays with temporary exhibitions and educational programs. Finally, there are tradeshows such as the annual Hanover Trade Fair, the Polymer Tradeshow – k – in Dusseldorf and Milan’s Furniture Show; each acts as a showcase for contemporary materials and design.

Material Sample Collections

Many individual designers and design houses assemble collections of materials

6. “Where do architects and designers get their ideas? The answer, of course, is mainly from other architects and designers” Stephen Bayley, *British Design Critic*, “Commerce and Culture,” Chapter 3 (1989).

7. *The ID Magazine* is a good example.

8. See, for example, *Byars* (1995, 1997a,b, 1998).

9. *The International Design Year Book* (1998, 1999); *The ID Magazine Annual Design Review* (1998, 1999, 2000).

10. See, for example, the catalog of the MOMA exhibition “Mutant Materials” (Antonelli, 1995), or that mounted by Material Connexion called “Materials and Ideas for the Future” (Arredo, 2000).

Material collection	Headquarters	Online
Material ConneXion	New York	www.materialconnexion.com
Materials library	London, UK	www.materialslibrary.org.uk
Central Saint Martins College	London, UK	www.arts.ac.uk
mâtério	Paris, France	www.materio.fr
Rematerialize	Kingston, UK	www.kingston.ac.uk
Materia	The Netherlands	www.materia.nl
Modulor	Germany	www.modulor.de
Matdat	USA	www.matdat.com
Matbase	Netherlands	www.matbase.com
Transmaterial	USA	www.transmaterial.net

3.12 Material collections

Libraries of material samples come and go. Those listed here were current at the time of writing.



3.13 Mood Boards

A mood board for a pen that is waterproof – designed to be used on the beach, with strong connections to the lifestyle of surfing.

not just metals, plastics, and ceramics but also weaves, finishes, coatings, and shapes – materials that have, in various ways, been processed (3.12). The physical nature of the samples is the key point: new ideas – inspiration – can come more readily from handling (not just visualizing) a material. Familiar materials carry associations that derive from their traditional uses: polished wood – the sense of warmth, civilization, discrete luxury; brushed aluminum – the sense of clean mechanical precision, and so forth. But the use of familiar materials in an unfamiliar way is also a creative step. New materials, particularly, act as a trigger to inventive thinking, offering the potential for novel design. This is where maintaining a material collection becomes challenging. Most material development is driven by technical need, not by motives of industrial design, with the result that information does not readily reach the designer. Material information¹¹ services exist that carry large sample collections and offer web-based access to images

and suppliers, but not much more (3.12). There is a need for an accessible sample collection with links from the image and supplier to a larger file of aesthetic and technical data. We return to this point later in the book (see Figure 3.13).

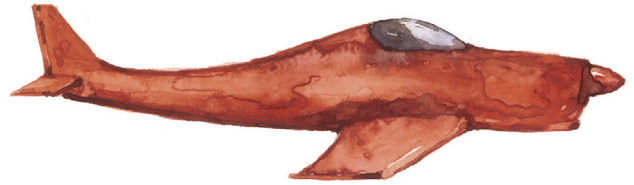
Nature as Inspiration

To “inspire” is to stimulate creative thinking. Inspiration can come from many sources. That for product design comes most obviously from other products and from materials and processes, particularly new ones. After that, nature is perhaps the richest source. The mechanisms of plants or animals – the things they can do and the way they do them – continue to mystify, enlighten, and inspire technical design: Velcro, non-slip shoes, suction cups, and even sonar have their origins in the observation of nature (3.14). Nature as a stimulus for industrial design is equally powerful: organic shapes, natural finishes, the use of forms that suggest – sometimes vaguely, sometimes specifically – plants and animals: all are ways of creating associations, and the perceived and emotional character of the product. Designs that are directly inspired by nature have a very unique point-of-view (3.15) and often surprising behaviors (like the not-so-sticky but super-adhesives that mimic gecko feet).

Creativity

Techniques for creative thinking work by breaking down barriers and forcing new angles of view. Some help the designer to escape from the view of the

11. An example is the subscription service of Material Connexion, www.materialconnexion.com.



3.14 Elements of Nature

Throughout history nature has provided a rich source of inspiration for designers.

“product” as it is now, seeking to see it in new ways. Others are ways of extrapolating ideas from the past and present to envisage new solutions for the future. Still others rely on the accumulation of information that relates to design challenge, slowly building a “scaffold” of ideas that becomes, when the last pieces are in place, the framework of the new design. All require work. Creativity, it is rightly said, is 1% inspiration and 99% perspiration.

Brainstorming, Mood Boards, Mind Maps

Brainstorming relies on the group dynamics that appear when participants express their ideas, however wild, deferring all value judgment until the process is over. Humor plays a role. A joke that works relies on a creative jump, an unexpected outcome, by-passing normal

reasoning. It switches the points, so to speak, deflecting thought off its usual rails onto a new track. It is the creativity of a good joke that gives pleasure, makes you laugh. Introducing it creates an environment for creative thinking. To work, brainstorming sessions must be fun and be kept short – experience suggests that one lasting more than 20 min ceases to be productive.

Mind-mapping can be a sort of personalized brainstorming in which ideas are placed on a page and linked as appropriate; these links are used to stimulate further thinking: “light-weight materials wood... cells... porous solids... foams. metal foams. titanium foam...?” Or it can be a map of a more considered sort (see below).

A mood board is a visual scrap-book, arranged on a large board placed where

3.15 Bone Chair

Joris Laarman created this nature-inspired chair using software that mimics the way in which bone reconfigures itself under load; Ross Lovegrove “Go Chair”, inspired by the curves of a bear skull.



the designer will see it easily. It takes of the form of a personalized, project focused collection of images, objects, or material samples, chosen because they have colors, textures, forms, features, or associations that might contribute to the design. Images of products that have features like those sought by the designer and images of the environment or context in which the product will be used act as prompts for creative thinking. Many designers confronted by the challenge of creating product character, to first buy examples of other product that have a surface finish, an association, a style that might be exploited in a fresh way. The mood board acts as a trigger for ideas both about choice of materials and about their juxtaposition.

More Formal Methods: Inductive Reasoning and Analogy

Inductive reasoning (Kolodner 1993) builds on previous experience. The starting point is a set of design requirements expressed as problem features. A match is then sought between these and the problem features of other solved problems, allowing new, potential solutions (“hypotheses”) to be synthesized and tested.

A central feature here is the library of previously-solved problems or “cases” – a “case” is a problem, an analysis of its features, a solution, and an assessment of the degree of success of this solution. The challenge in assembling the library is that of appropriate indexing – attaching to each “case” a set of index-words that capture its features. If the index-words are too specific the “case” is only retrieved if an exact match is found; if too abstract, they become meaningless to anyone but the person who did the indexing. Consider, as an example, the “case” of the re-design of an electrical plug to make it easy to grip, insert, and pull-out by an elderly person with weak hands. Indexing by “electrical plug” is specific; the case will be retrieved only if the “plug” is specified. Indexing under “design for the elderly” is more abstract, and more useful. Plugs are not the only thing elderly people find hard to use. Cutlery, taps, walking sticks, and many other products are adapted for elderly people. Examining their shapes and materials and processes used to make them may suggest new solutions for the plug.

Software shells exist that provide the functionality to create case-based



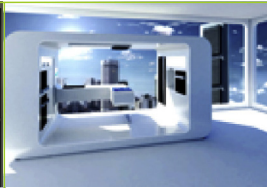



systems, but, for any given domain of problems, the library has to be populated.

TRIZ and the 9-Windows Method

TRIZ (standing for Theory of Innovative Problem-Solving – but in Russian) is the brainchild of the Russian patent expert Genrich Altshuller, distilled, so to speak, from his study of patents. He arrives 40 principles and 8 patterns of evolution for creating engineered products. There are disciples of his methods and there are non-believers. Be that as it may, one technique, the 9-window method claimed as part of the TRIZ tool-set, finds wide use as stimulus for creative thinking. The obstacle to innovation is, often, a preoccupation of the system as it is now. The 9-window method forces a view of the system on different conceptual scales and at times other than the present (3.16). It takes the form of a 3×3 matrix of initially empty boxes.

The system for which creative thinking is sought is put in the central box – it can be described in words or recorded as a schematic or an image it represents the system as it is now.

The horizontal axis is time past, present, and future (it helps to make this quantitative, thus: 1 year ago, now, 1 year from now; or 50 years ago, now, and 50 years hence). The vertical axis is that of scale: subsystem (the components of the system) in the bottom row, above this the system scale, and above that the super-system of which the system is a part or in which it must operate. There are several ways to use the past, present, and future columns. One is to ask: what are the antecedents of the system (subsystems, super-system), and what, ideally, would you like these to become in the future? Another is to ask: if you could have designed the system differently (in the past) what would you have

	Yesterday	Today	Tomorrow
Super-System			
System			
Sub-System	<p>MATERIALS: Copper, Brass</p> <p>HEAT SOURCE: gas flame</p>	<p>MATERIALS: Polypropylene, Stainless steel</p> <p>HEAT SOURCE: grid electricity</p>	<p>MATERIALS: Ceramic? Insulating polymer sandwich?</p> <p>HEAT SOURCE: In-house fuel cell? Heat pipe? Microwave heating?</p>

3.16 Triz Method

The 9-window method applied to the re-design of an electric kettle.

done? What can I do now to enhance the system? What – given time – should I aim for in the future? A third is to ask: where are we now? Where have we come from over the last 5 years? Where do we wish to be 5 years from now? The idea is to encourage a view of the problem from in front and behind, and from above and below, allowing a freedom to zoom in and out. The method is sufficiently useful that an example is justified.

Figure 1 shows the 9-windows. The product to be re-designed is the electric kettle in the middle box of the “Today” column. The kettle has long history. It evolved from kettles that looked like that in the middle box of “Yesterday.” The aim is to design a kettle for “Tomorrow.”

Think first of the super-system in which the kettle will be used. The top row suggests the size, color, décor, and equipment of kitchens from yesterday and today, and a guess at how these might look tomorrow – increasingly hi-tech but increasingly small. The re design must accommodate this evolution – it is the environment in which the kettle-users will live. The ascetic, rectilinear design of the future kitchen suggests a compact, cuboid kettle with similar minimalist aesthetics.

The bottom row reports aspects of the technology of kettles that have changed radically, notably choice of materials and ways of introducing heat. What opportunities are presented by new materials and heat-transfer methods? Advanced ceramics and glasses are now used in many demanding applications. They have the merit of extreme durability. Heat-transfer technology has changed

greatly. It is well to remember, too, the emerging priorities, globally, are those of conserving energy, mineral resources, and water, and the prerequisites of environmental and economic responsibility. How can emerging technology be used to adapt the new kettle to meet these expectations?

The 9-window analysis broadens the horizons of thinking. It gives doors out of the box in which we started – that of a single focus on today’s kettle. Better kettles may not strike you as an elevated goal. Replace it, then, by personal transport (the car) or communication (what comes after e-mail era) or managing your data (handwritten accounts – excel spread sheets with search – Big Data clouds with data-mining?).

A Culture of Ideas

Where do good ideas come from? They don’t just “happen.” Rather, they emerge from a fascination with a problem, an obsession almost, that sensitizes you to any scrap of information that might, somehow, contribute to finding a solution. Combine this with reading and discussion, loading up the mind, so to speak, with background information and with solutions to related problems that, you sense, might be relevant. The human mind is good at rearranging bits of information, seeking patterns, often doing so subconsciously (we have all had the experience of waking in the night with the answer to a problem that, the previous evening, had no solution). It is like finding a route across previously unmapped territory. The route is what is wanted, but to find it you have to map,

at least approximately, the territory as a whole. Or (another analogy) it is like building a scaffold out of many scaffold-poles to reach a remote and awkward roof-top. Only when the last pole is in place can you reach the top; till then it was inaccessible. To repeat: good ideas don't "happen"; they emerge by giving the mind the means to find them.

The subject of materials is one that is rich in unanswered questions. Building a mental library of relevant "bits" of information, cultivating it by allowing reflection-time to try out various arrangements of the bits, allows them to finally fall into a pattern that gives new insight or suggests a new product.

Sketching and CAD

The form of a new product first takes shape by sketching – freehand drawing, freely annotated, that allows the designer to explore alternatives and record ideas as they occur. Sketching is a kind of image-based discussion with oneself or with others – a way of jotting down ideas, rearranging and refining them. Only at a later stage is the design dimensioned, drawn accurately, and coded into a surface modeling package. Modeling software¹² allows the display of projections of the product and experimentation with visual aspects of color and texture. But designers emphasize that it is not these but the act of sketching that stimulates creativity.

Model-Making and Prototyping

A design evolves through models; these models are an important means of

communication between industrial and technical designers, and between the designers and the client for whom the product is to be made. Preliminary models, often made of polymer foam, plaster, wood, or clay, capture the form of the product; later models show the form, color, texture, mechanisms, and weight. Models allow the product to be handled (if small) and viewed from multiple angles (particularly important when large). Rapid prototyping has transformed the later stages of model-making, allowing a CAD file from a modeling package to be downloaded and converted directly into a wax or polymer model.¹³

Case Studies from IDEO

In order to present real expressions of the combination of materials and design, we have included a few case studies from IDEO (www.ideo.com) as part of this chapter. These case studies do not follow the structure that is introduced later in Chapter 8, but rather, they are intended to provide inspiration to think about materials and design as part of the products we intend to design or re-design. IDEO's design philosophy, design process, and design teams are organized with a sort of structured chaos so that it is able to balance many elements for inspiration and problem-solving. In the case studies that follow we focus on the material and manufacturing details and idea of materiality that each designer is intending to create.

13. Profiles of rapid prototyping systems will be found in the Reference Profiles at the end of this book.

12. Pro-engineer's Solid Works 2001 is an example of a solid modeling program for mechanical engineers and designers with the ability to download files for rapid prototyping.

3.17 Structure of 3D Fabric

A chair injection molded with glass-filled nylon wrapped with 3D fabric that moves with you and allows new ways of working (Image courtesy of IDEO).



Steelcase i2i Chair

In 2008, Steelcase and IDEO collaborated on the strategy and design of workspace furniture and user experiences for evolving business environments. As part of this project, IDEO developed elements of materiality that connect the surface and the structure to allow a variety of options for sitting, moving, and working in a chair. The design team constructed a

flexible open structure in injection molded nylon and surfaced it with a 3D fabric woven from polyester fibers (3.17). The sitting surface is wider than most chairs and the plastic and fabric flex as you move. The combination of these two materials replaces traditional upholstered foam and creates an entirely unique way of thinking about dynamic comfort.

3.18 Molded Melamine

A simple structure for your kitchen, your bathroom, and your trash. (Image courtesy of IDEO).



OXO Trashcan

In 2006, OXO partnered with IDEO to develop a line of waste bins. As part of this project, IDEO developed elements of materiality that express durability and simplicity. The design team molded the outside surface of a series of products in melamine. For these trashcans the shape is easily compression molded with large draft angles, thick walls and a simple handle (3.18). The surface of these wastebins is harder than traditional plastic so they resist scratching and have a uniquely ceramic quality that is appropriate in the kitchen and in the home.



3.19 Molded and Die-Cut Paper Pulp

Packaging as an expression of brand and ingredients (Image courtesy of IDEO).

Pangea Organics Packaging

In 2006, Pangea Organics, a Boulder, Colorado-based company that sells 100% organic soaps, lotions, and facial care products, was reaching the 4 year mark when founder and CEO Joshua Onysko approached IDEO to help redefine its brand expression. As part of this project, IDEO developed elements of materiality that would express the brand's connection to sustainability and organic ingredients. The design team explored the use of molded paper pulp that is more ordinarily seen as egg cartons are. The final packaging was a compostable soap box that had seeds imbedded in the material itself, so that it will grow into a new plant if it is composted in the backyard or anywhere else (3.19). This packaging served as a protective case for the soap, a point of purchase display, and a platform for communication details.

Levi's Customized Buttons

In 2009, IDEO worked with Levi's to realize a customized button-fly as part of a larger

Levi's initiative, the "Live Unbuttoned" campaign to re-launch the 501 brand and target the young and hip. As part of this project, IDEO developed elements of materiality that connected to a core element of the Levi's brand and could be used with existing buttons. The design team considered a button cover made of two stainless steel pieces that snap onto (and cover) the existing buttons on the 501 button-fly. These buttons provide a blank canvas for artwork that expresses an individual's personality or daily fashion (3.20).

3.20 Metal Injection Molded (MIM) Stainless Steel

A button that lets you customize your 501s (Image courtesy of IDEO).





3.21 Stamped Aluminum Buttons

A mobile device for easy and beautiful organization (Image courtesy of IDEO).

3.22 Injection Molded SAN

A salad spinner that let's you see your lettuce and allows easy storage (Image courtesy of IDEO).

Handspring Organizer

In 2000, Handspring's new addition to its popular Visor line of handheld organizers was the Visor Edge, an elegant device that was only 7/16 of an inch thick (3.21). As part of this project, IDEO explored elements of materiality that would create a new form and define a visual identity to express the thinness of the product. The design team explored stamped aluminum components for the body

and the buttons; the aluminum could be anodized in three different colors and a integrated hinge allows the cover to protect the display and be easily stored. The final product was portable, comfortable, attractive, stiff, and robust.

Zyliss Salad Spinner

In 2004, IDEO worked with Zyliss USA to design a large range of kitchen tools. As part of this project, IDEO developed elements of materiality that highlight the visual display of the lettuce that is spinning and stored in this container (3.22). The design team explored injection molding a tinted SAN (styrene-acrylonitrile) plastic. The lid and the container are both transparent and are molded without any additional structural elements on the inside for easy cleaning; on the top surface, a perfectly flat lid, designed for easy stacking, molded in white ABS plastic, conceals the engine components – an amazingly efficient mechanism that allows easy spinning and quick stop.

Lufthansa Wireless Remote

In 2003, IDEO collaborated with Lufthansa Technik ag to produce the industry's first wireless handheld remote for in-flight entertainment and cabin management systems (3.23). As part of this project, IDEO developed elements of materiality that suggest a uniquely exclusive hand-crafted aesthetic. The design team built details that leveraged the ceramic-like surface of this material and its inherent translucency; LED lights glowed softly to locate the device in a dark space and the exterior was wrapped





3.23 Machined Ceramic-Filled Plastic ("Corian")

A handheld wireless remote for a super-lux air travel experience (Image courtesy of IDEO).

with metal to highlight and mechanically support the white surface.

Samuel Adams Beer Handle

In 2004, IDEO worked with The Boston Beer Company, designing a new bar tap handle for Samuel Adams beer (3.24). As part of this project, IDEO developed elements of materiality that connect the function of the handle (pouring beer) to the iconic qualities of the brand (authenticity, reliability). The design team explored a contemporary design that could be easily seen from a distance. Molded translucent blue acrylic provides a large surface for branding and a sense of luxury; its form is both ergonomic and expressive.



3.24 Injection Molded Acrylic

A tap handle that stands out at a distance and communicates the brand (Image courtesy of IDEO).

Conclusions

The picture that emerges is that of the designer's mind as a sort of melting pot. There is no systematic path to good design, rather, the designer seeks to capture and hold a sea of ideas and reactions to materials, shapes, textures, and colors, rearranging and recombining these to find a solution that satisfies the design brief and a particular vision for filling it. Magazines and yearbooks, material collections, museum exhibitions, tradeshow, and the designer's own experience provide the raw ingredients; the designer permutes, modifies, and combines these, stimulated by brainstorming or free discussions and astute observation of what other designers are doing. This involves drawing freely on memories or images, combining aspects of each, imagining and critically examining new solutions – a sort of self-induced virtual reality. The brain is good at storing an enormous number of images, but is poor at recalling them in detail without prompts or specific triggers.

These prompts can be created by using stored images and visual information about materials and products, provided these are indexed in ways that allow rapid recall. Indexing, then, is key to ordering material and process information to provide a design tool. To do this effectively, indexing must be sufficiently abstract to capture relationships, yet be sufficiently concrete to be easily understood by a novice user. If this can be achieved, a framework for organizing and manipulating the attributes of materials and their role in technical and

industrial design becomes possible. The ultimate aims of this creative framework might be:

- To capture and store material and process information of the sort found in magazines, yearbooks, and exhibition-based publications.
- To present information about materials and processes in a creative format that is relevant to product design.
- To allow browsing of potential materials or processes via hypertext links or free-text searching.
- To allow retrieval of “bits” of information about the technical and perceived attributes of materials, processes, and the products they create.

These all lie within the scope of present-day software engineering, but they require more thought about the best way to organize information for designers. We will consider them further in Chapter 7.

Further Reading

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Ashby, M.F. (2005) "Materials Selection in Mechanical Design," 3rd edition, Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-6168-2. (A text that complements this book, presenting methods for selecting materials and processes to meet technical design requirements and presenting a large number of material property charts.)

Beylerian, G.M. and Osborne, J.J. (2001) "Mondo Materialis," The Overlook Press, Woodstock and New York, NY, USA. ISBN 1-58567-087-1. (Creative use of materials from 125 architects and designers, presented as collages, in large format and full color. The original collection was created for a 1990 exhibition.)

Burge, S. (2011) "The systems thinking toolbox" <http://www.burgehugheswalsh.co.uk/uploaded/documents/AF-Tool-Box-V1.o.pdf> (An introduction to Affinity thinking.)

Byars, M. (1995) "Innovations in Design and Materials: 50 Chairs; (1997) "50 Lights" and "50 Tables;" (1998) "50 Products," RotoVision SA, Switzerland. ISBN 2-88046-264-9, 2-88046-265-7 and 2-88046-311-4. (Lavish color illustration with minimal text cataloging the designer, material, and processes surrounding groups of 50 contemporary products.)

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Ferguson, E.S. (1992) "Engineering and the Mind's Eye," MIT Press, Cambridge, MA, USA. ISBN 0-262-06147-3. (A largely historical sweep through design history since 1700, highlighting past and present deficiencies, and emphasizing visual imagination above pure analysis in the act of design.)

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Chapter 4

Materials: The Stuff That Surrounds Us

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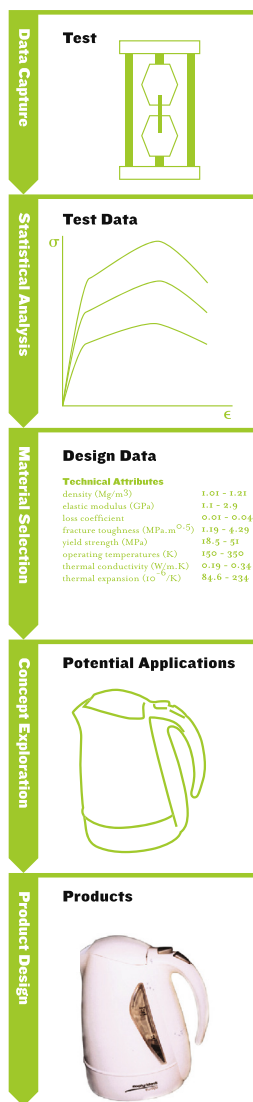
Materials are the stuff of design. When we speak of “information” for materials what do we mean? [Figure 4.1](#) illustrates the steps involved in moving a material from the laboratory into a successful product. Tests yield raw data. These are distilled, via appropriate statistical analyses, into data for “material properties”: values for properties on which design can safely be based (typically, 3 standard deviations below the mean). A material may have attractive “material properties” but to make it into a product requires that it can be shaped, joined, and finished. The characterization of the material

is summarized in a table of such information ([4.1](#), center). This process enables safe, technical design of a product – it is focused on the engineering dimension, so to speak.

That is only the start. Once made, the product will be used – the choice of material is influenced by the nature of the user: children, perhaps, or travelers, or the elderly. Does it comply with legislative requirements that the product must meet (FDA approval, perhaps, or requirements limiting flammability, noise, vibration, or bio-compatibility)? Would it survive the use, and misuse it will encounter in service? Is it toxic? Information for this – the dimension of

use – is as important in guiding selection. People are the end-users for most products and we need to consider their needs early in the design process. There are human needs beyond what we have listed here, but those are considered later in this chapter.

There is more. Manufacturers and their customers are searching for solutions that are sustainable and green. In the world of manufacturing, this is documented by a factory’s qualification as ISO 9000 or 14000 – meaning that it has established quality standards and procedures of environmental auditing and responsiveness. This, the environmental dimension, requires yet another layer of



4.1 Confidence in New Materials

The steps in moving a material from the laboratory to a successful product.

materials information, one relating to product manufacture, use, and disposal. And even that is not the end.

The industrial design of a product is as much a part of its creation as any other. The characteristics of a material that contributes to industrial design, though harder to document, are as important as the more technical properties. This – creating emotional connection and doing good design – requires a fourth dimension of materials information: that relating to aesthetics and personality.

Given these five attributes, rational and emotional design with materials becomes possible. Carrying the design into production depends – as we said in Chapter 2 – on investment, attracted by a successful business case. But we have enough to discuss without that. Here we explore the five dimensions of materials information: engineering, product use, the environment, aesthetics, and emotion.

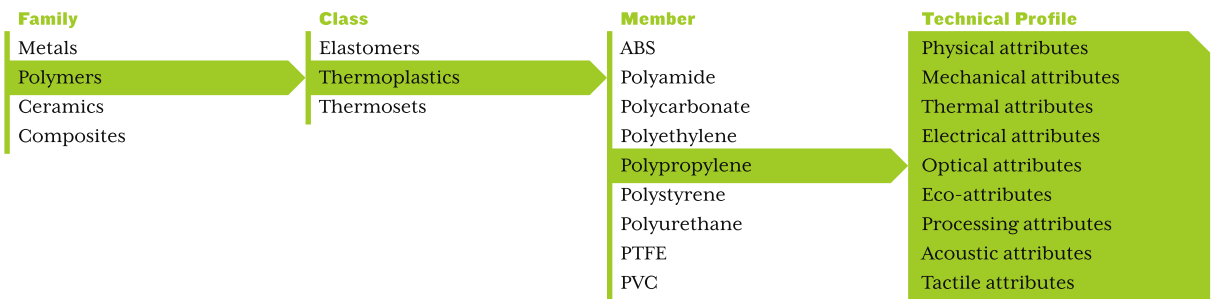
The Engineering Dimension: Technical Attributes

The scientific study of materials – materials science – seeks to understand the fundamental origins of material properties, and, ultimately, to manipulate them. It has had remarkable success in doing both. The origins of many material properties derive directly from the atomic and electronic structure of the material: among these are density, stiffness, thermal and electrical conductivity, optical transparency, and many others.

These are now well understood, and can, within the limits imposed by the laws of physics, be manipulated. Composites, one of the great technical advances of the last 50 years, combine the properties of two very different materials: polymers and carbon fibers in sports equipment, elastomers and steel in car tires, metals and ceramic fibers in aerospace components. Here, too, the scientific understanding is deep and the ability to “design” materials is considerable.

Material science has developed a classification based on the physics of the subject (4.2). It is not the only one – architects, for instance, think about materials in other ways.¹ The science-based classification emerges from an understanding of the ways in which atoms bond to each other, and (in the case of composites) how mixtures of two different materials, each with its own attributes, behave. But science is one thing, design is another. Is the science-based classification helpful to the technical designer? To explore this further we must first look at the technical attributes of materials. The classification of 4.2 – Family, Class, Member – is based, at the first level, on the nature of the atoms of the material and that of the bonding between them (e.g. “polymer”), at the second level on its variants (e.g. “thermoplastic”), and at subsequent levels, the details of its composition. Each member has a set of attributes that quantify its physical, mechanical, thermal, electrical, and optical behavior – what we will call its technical profile.

Open a handbook or search the web, seeking a material by name, and you will



find technical data. This information is largely numeric: values for modulus, strength, toughness, hardness, thermal conductivity and expansion coefficient, electrical resistance, and so forth (4.3), backed up with a little text-based information on corrosion resistance and wear. These are the data needed for technical design – for the calculation of safe loads, temperatures, heat fluxes, and operating life. The most useful classification of materials for technical design is one that groups materials that have similar profiles of these technical attributes. But what do we mean by “similar”?

Mapping Technical Attributes

Asking if two colors are “similar” can be answered by comparing their wavelengths. But if by “similar” you mean a larger set of properties, you are asking for something more difficult: recognition of a pattern of behavior. The brain is better at pattern recognition when the input is visual rather than text-based. So: how can we make technical attributes visible? One way is by plotting them in pairs, to give a sort of map of where they lie. Figure 4.4 is an example. Here the first two of the attributes from 4.3 –

elastic modulus, E , measuring stiffness, and density, ρ , measuring weight – are mapped, revealing the layout of the E - ρ landscape. The dimensions of the little bubbles show the range of moduli and density of individual classes of material; the larger envelopes enclose members of a family. Metals cluster into one part of the map, polymers into another, ceramics, woods, foams, elastomers into others. Like maps of a more conventional kind, it condenses a large volume of information into a single, easily readable, image².

What do we learn? That members of each of the families of 4.2 cluster in a striking way. They do, when judged by these two engineering properties, have distinctive similarities, allowing them to be grouped and to be distinguished from other families that group elsewhere. There is, however, overlap – the lightest, stiffest metals overlap with technical ceramics and composites; elastomers overlap with polymers – here the separation is ambiguous.

But those were only two technical attributes. Materials have many more. Plotting them³, you find the same groupings, but the overlaps are not the same.

4.2 Classification of Materials

A classification of materials based on a scientific understanding of the nature of the atoms they contain and the bonds between these atoms. The final column shows a list of possible attributes for a specific material.

1. *Cardwell et al. (1997), for example, suggest a radically different classification - one based on familiarity rather than physics: unfamiliar, familiar, contemptible (!), unknown, and unknowable.*

2. *The labels that are used in these maps are shortened for the sake of space: fPU is flexible polyurethane foam, rPU is rigid, ocPU is open cell, ccPU is closed cell, tsPolyester is thermo-setting polyester, tpPolyester is thermoplastic.*

3. *There are maps like 4.2 for many other engineering properties of materials. They can be copied without restriction from Ashby (1999), or downloaded free of charge from www.grantadesign.com.*

4.3 Technical Profiles

Selected technical attributes for polypropylene.

4. The methods of multi-dimensional scaling are well described in the little book by [Kruskal and Wish \(1987\)](#).

Physical Attributes	
Density, kg/m<	900–910
Mechanical Attributes	
El. modulus, gpa	1.14–1.55
Yld. strength, mpa	31–35
Tensile strength, mpa	33–36
Comp. strength, mpa	37–45
Elongation,%	100–350
Toughness, kj/m€	10–11
Fatigue limit, mpa	11–15
Hardness, Vickers	9.2–11
Thermal Attributes	
Max use temp., c	90–105
Th. conductivity, w/m.c	0.11–0.12
Th. expansion, /c. 10-fl	145–180
Molding temp., c	210–250
Electrical Attributes	
Dielectric constant	2.2–2.3
Dielectric loss,%	0.05–0.08
Resistivity, ohm.cm	3.10 ²² –3.10 ²³

If the classification you want is one based on technical, “engineering” attributes then it looks as though the right one is the one the scientists propose.

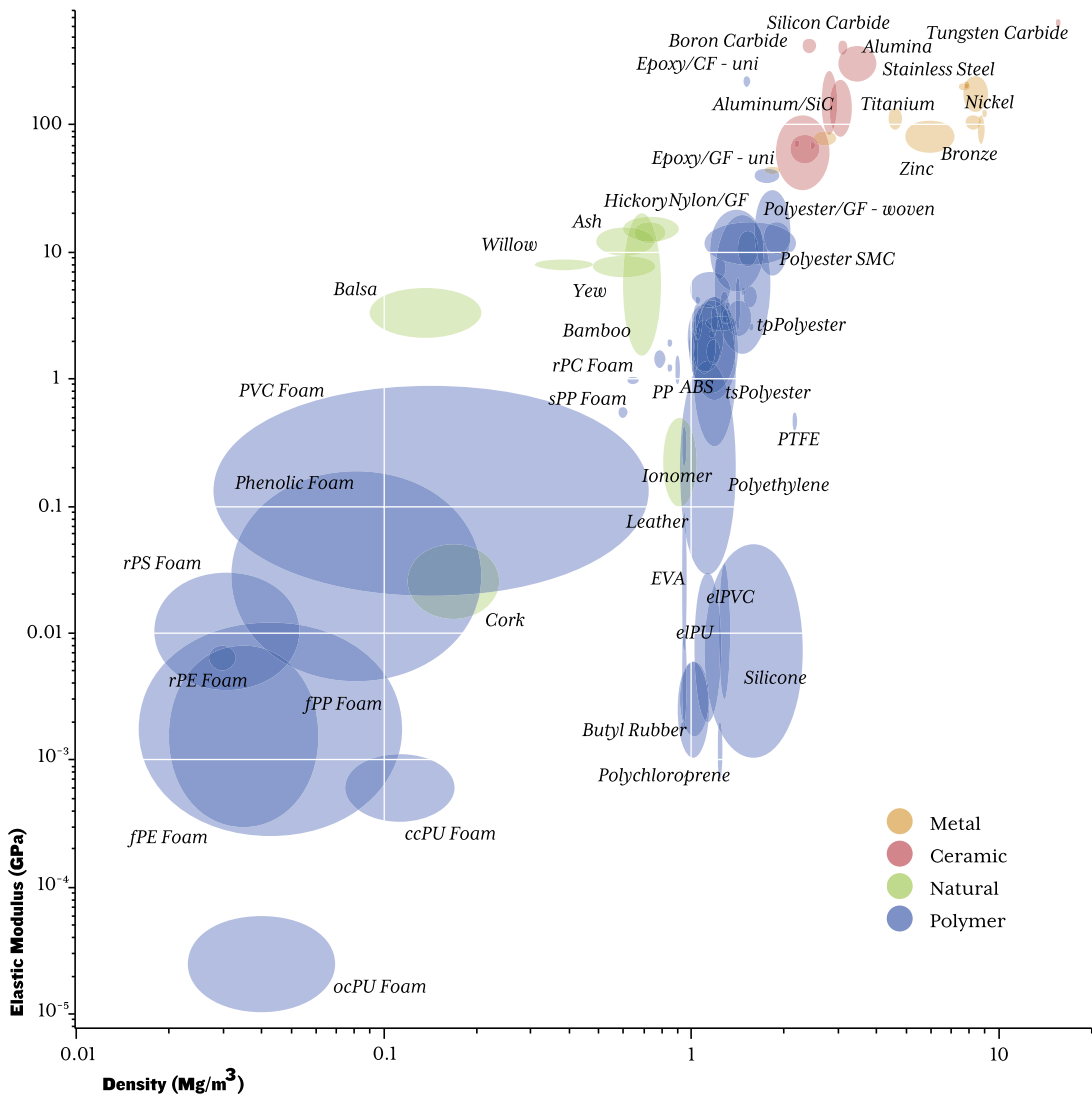
Maps like that shown in 4.4 can suggest composites and blends of two materials. The most common composites are fiber or particulate-reinforced polymers. Glass fiber is stiffer and denser than nylon; adding glass fibers to the nylon gives a material with stiffness and

density that lies somewhere in between. Polymer blends, similarly, have properties intermediate between those of the pair of polymers that were blended. The maps allow this to be visualized, suggesting combinations that might meet a specific need.

So visual presentation of data can reveal similarities that are hard to see in other ways. And that makes you wonder if you could go one step further and, instead of mapping many separate pairs of attributes, find a way of combining them all to make a single super-map – a global overview. Well, yes and no. Yes, there is a way of doing this. But what it reveals is not so clear. Still, it’s worth looking at. It is called multi-dimensional scaling, or MDS.⁴

MDS is a way of revealing similarities and differences between members of a group, using information about many attributes, not just two. Applied to materials, it works like this. First, calculate the “distance” between each material and every other in the group, taken in pairs. “Distance” is a measure of dissimilarity: if all the attributes of two materials are identical, the distance between them is zero. If all but one are identical, and the odd one out differs by 10 units, the distance might be given the value 10. If all are different, and by varying degrees, each difference is given a value and all the values are aggregated to give a single number: this is the overall “distance” between the two materials. The output of this step is a table, showing the distances between each material and every other.

You can learn something by looking at this table, picking out groups of



materials that are separated by the shortest distances. But when the number of materials is large, this is hardly a visually inspiring task. So there is a second step – that of manipulating this table to make a “distance-map.” It involves a kind of optimization technique that is best explained

as follows. Suppose you had only three materials, and had calculated, for as many attributes as you wished, the three distances between them. You could then make a picture on which you placed a dot and called it “material 1,” and then a second dot, at a length equal to the material

4.4 Elastic Modulus and Density

A chart of Elastic Modulus and Density for materials, showing the clustering of metals, polymers, ceramics, foams, woods, etc. (CES Edu, 2009).

5. Many arbitrary decisions are involved. “Distance” can be measured and aggregated in more than one way. An example: normalize all data to a set range – say -10 to 10 – calculate the individual distances for each attribute of a material, then aggregate by forming the root-mean-square of these (Euclidean aggregation). Minimizing the stretch and squeeze, too, allows many alternatives. An example: minimize the root-mean-square of the deviations of the stretched or squeezed distances from the values they should, ideally, have. Sounds sensible, but both examples contain implicit assumptions about the relative “weights” of small and big differences, and about the extent of acceptable distortion. If you want to use the method, read [Kruskal and Wish \(1987\)](#) first.

6. Material suppliers provide datasheets for their products, though the content is often limited. More comprehensive data are tabulated in handbooks such as those published by ASM International, Butterworth-Heinemann and McGraw-Hill, some now available in searchable CD format. Software systems such as that of Granta Design (CES Edu, 2009) offer fast access to some thousands of technical datasheets in standard format, compiled from many different sources. Increasingly, technical data can be found on the worldwide web sites such as [www.matweb.com](#).

1 – material 2 distance that you called “material 2,” and then a dot for material 3, making a triangle, so positioned that it was just the right distance from 1 and 2.

Fine. But now add a fourth material. In general, you can’t find a place where it exactly fits – where its distances from 1, 2, and 3 are all correct; it’s a consequence of the two-dimensionality of the picture. But suppose you could stretch some of the distances and squeeze others, you could go on doing so until there was a position in which the fourth material would fit – although the map is now distorted, an approximation, no longer an exact visualization of the distances. And you could go on adding more and more materials, each time doing a bit more stretching and squeezing. This, you might think, would lead to an ever more distorted map, but if you had an algorithm that minimized, at each step, the total stretch and squeeze, you could keep the distortion to a minimum. And that is exactly what multi-dimensional scaling does.⁵

The maps that emerge have to be interpreted with caution – they are approximations. The “distance” measure on which they depend rolls many attributes into a single number; and in doing so it throws away a great deal of information (“does a distance of 20 mean that all attributes differed a little, or that most were identical and one was very different?”). But the method does produce interesting pictures, in which clustering is clearly evident.

Figure 4.5 is an example. It is an MDS map for engineering materials based on 15 of their mechanical and thermal attri-

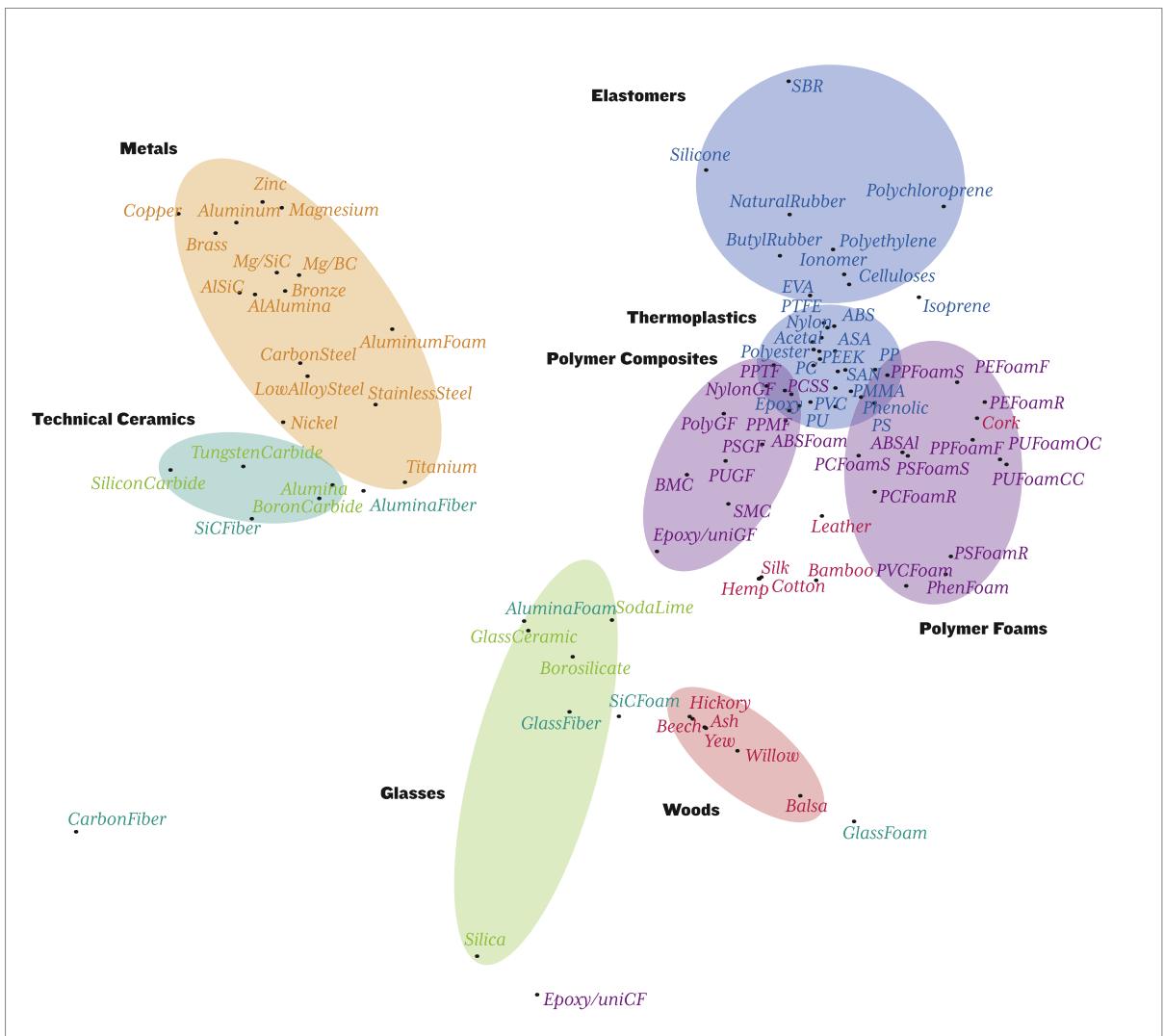
butes. Ceramics, metals, and polymers each fall into separate groups; and within polymers, thermoplastics and elastomers form overlapping groups. The analysis has led to groupings that in most ways resemble the families and classes of material science.

So, for technical attributes, the classification of 4.2 is the one we want. Classification is the basis of indexing – an essential step in cataloging materials information. We will return to indexing in Chapter 7. Here we simply note that, for technical attributes, we have a good basis, and we turn briefly to the uses of technical attributes in product design.

Using Technical Attributes

The success of a product in the marketplace depends heavily, we have argued, on its industrial design – on its appeal, visually and emotionally, to the consumer. But this presupposes that it works – that it performs its technical function well, safely, and at acceptable cost. The responsibility for this rests with technical design, and technical design relies on sound material data.

The characterization of materials for technical design – the top half of 4.1 – is well developed. Datasheets like those of 4.3 are widely available.⁶ The information they contain provides the necessary inputs for technical design, using the standard methods of engineering: stress analysis, thermal analysis, optimization methods, and simulation. All of these are supported by sophisticated software tools. This sounds reassuring – and it is – but one real challenge remains. You can find technical data for a material



if you know the one you want. But how do you make that choice? And how do you make sure it is compatible with the other “dimensions” with which this chapter started? We return to this question in Chapter 7. But first we examine the other dimensions and the materials information needed to address them.

Usability: Ergonomics and Interfaces

Everyone knows the TV with the switch so cleverly integrated into the styling that it can't be found in the dark, the tap too smooth for soapy fingers to turn, the hairdryer so noisy that you can't hear

4.5 Multi-Dimensional Maps: Mechanical Attributes

This map shows similarity between materials based on their mechanical attributes (Data from CES Edu, 2009).

4.6 Human Measurements

Average attributes of European and North American men and women of working age.

Characteristic	Man (18–40)	Woman (18–40)
Standing Height, m	1.63–1.85	1.54–1.76
Seated Height above seat, m	0.84–0.96	0.79–0.91
Seat Width, m	0.33–0.40	0.35–0.43
Forward Reach, m	0.77–0.92	0.60–0.75
Shoulder Width, m	0.42–0.50	0.38–0.46
Eye Height, Standing, m	1.52–1.74	1.44–1.65
Body Mass, kg	60–94	44–80
Head Mass, kg	1.4–1.7	1.25–1.6

the phone... well, the list is long. Each of these products works but has a poorly designed interface – it is difficult to use. Well-designed products not only work, they are convenient, safe and easy to interact with – they are user-friendly.

The design of a product’s interface has three broad aspects: the first concerns the matching of the product to the capabilities of the human body; the second, matching to the reasoning power of the human mind; and the last, matching with the surroundings in which the human lives and works. Collectively, these are known as human factors and their study is called ergonomics, interface design, or human-factor engineering, which we now examine.

Anthropomorphics and Bio-Mechanics

During World War II it became apparent that the effectiveness of service men depended strongly on the ease of use of the increasingly complex equipment on which they had to depend. This led to the study of *anthropomorphics* – the measurement of the size and shape of the human body – and of *human bio-mechanics* – the analysis of the

movement, forces, power, and stamina of which the body is capable.

Figure 4.6 lists some of these for European and North American populations. Physically, people vary in size and strength. As a yardstick, designs often use ranges that bracket 90% of the mature population of working age, and it is this range that appears in these tables. They define what might be called the Standard Design Person. In design for usability, these characteristics are treated as constraints: the product should accommodate any person with the dimensions and physical capabilities that lie within these ranges. Increasingly, in the workplace, these constraints must be met to conform with legislation intended to prevent undue fatigue or muscle strain and the accidents they cause.

But there is a story, relevant at this point, of the man who invented a shaving machine. You clamped it to your face, pressed the button, and – hey presto – you were shaved. When asked whose face it fitted he said it fitted the standard face. But what happened if someone who used the machine did not have a standard

face? After they've used my machine, he said, they will.

So the idea of a standard person is a little ridiculous. For true usability, equipment must be matched to the capabilities of the individual (4.7), not to some average. Nowhere is this matching more evident than in the design and marketing of sports equipment. Here products are carefully tuned to the bio-metric and bio-mechanical characteristics of the individual athlete or sportsman, and doing so has become a very big and profitable business. These however are not the only groups that require special attention. Others with Non-Standard Design Bodies (meaning that they lie outside – sometimes far outside – the ranges of the previous tables) include children, the disabled, and the elderly. Their needs, often neglected in the past, are now more widely recognized and designing to meet them is seen as a priority.

Materials have a role to play here. Heavy objects, often a source of physical strain when lifted or moved, can be made lighter by the use of light metal alloys, polymers, and foam-cored sandwich structures. Elastomers can provide grip where it is needed, polymer gels and foams allow soft tactile surfaces, and woven and non-woven fabrics conform to the body shape. Molded shapes that fit well in the hand and have smooth rounded corners that do not catch on clothing reduce the risk of accidents. Differences in size can be accommodated by using materials that allow adjust-ability – Velcro, demountable adhesives, elastomers.



4.7 Ergonomic Design

The control center of the forklift, designed to make complex maneuvers as intuitive as possible (Image courtesy Ergonomic Systems Inc.).

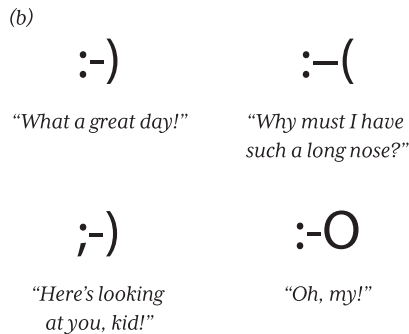
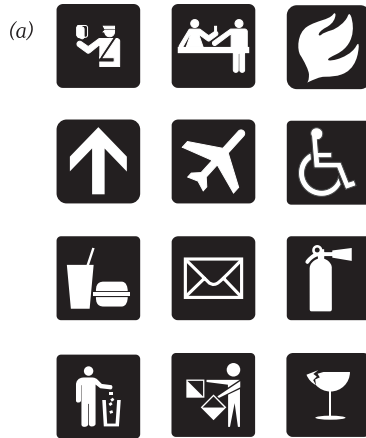
All this is straightforward. But products interact with their operators in other ways – ways that require the communication of specific information.

Information Management

The products with which we interact today are more complex and have more functionality than at any time in the past. Much of the functionality now derives

4.8 Icons and Emoticons

Visual triggers of direction in our everyday life and of emotion (in electronic text).



7. Caution is needed here – the interpretation of an icon can depend on culture. A knife-and-fork icon indicating “restaurant” could be meaningless to someone who eats with chopsticks.

8. The same is not true of text in a book. A typeface such as Times, with serifs – the thin horizontals that terminate the verticals – leads the eye more easily along and between lines.

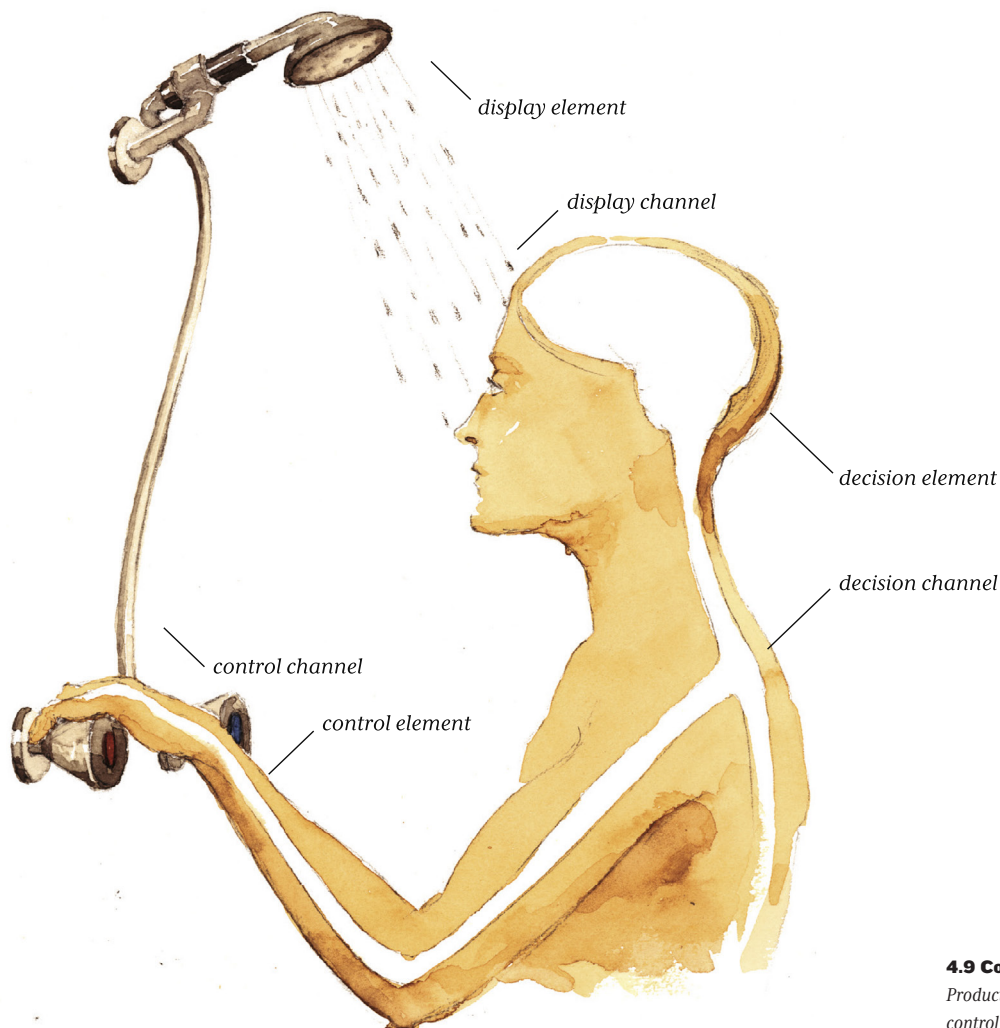
from, or is controlled by, electronics. Electrons, unlike simple mechanical things, are invisible and give few clues of what they are up to or that they are responding to the user’s wishes. Thus two sorts of communication must be built-in to the overall design – the passive one, indicating function, and the active one, indicating response to an input.

The first need is met by clear icon or pictogram-based identification. Icons (4.8) are easily read and, in a world of international trade and travel, have the considerable asset that they are language independent.⁷ Emoticons (4.8) – icons adapted to electronic messaging systems

– are based on the specific combinations of key strokes and can be interpreted as emotions. When complete words must be printed on the surface of a product, experiments show that the best legibility is given by a *san serif* typeface such as Helvetica or Arial, the use of lower-case letters except for initials, and high contrast.⁸

A person operating a device is part of a closed control-loop (4.9). Such a loop requires, first, one or more *displays* that document its current state. Visual displays are the most efficient way to transmit this information accurately, though for urgent warnings, sound is better. Second, the loop requires *control elements* or input methods. Push buttons, knobs, and levers have been largely replaced by keyboards, mice, laser pointers, touch-sensitive screens, and speech recognition systems. The inputs are interpreted by the device, which then reacts to them. The third requirement is an *indicator* – visual, tactile, or acoustic – that the input has been received; without it the operator has no immediate confirmation of acceptance and may mistakenly repeat or override the operation. The remaining element of the loop – that of *decision* – is provided by the operator.

Here it is materials for sensors, actuators, and displays that are important. Sensors are often based on piezo-electric materials, thermal sensing materials, and light sensing materials (photodiodes). Actuator materials include muscle (the old way of activating everything), bimetallic material, shape-memory alloys, piezo-electric, electro-strictive, and magneto-strictive materials, and polymer gels. Thermo-chromic materials



4.9 Control and Feedback

Products and users for closed-loop control and feedback system.

change color on heating; electro-chromic materials do so when a field is applied. Flexible materials can be shaped to give bi-stable key response, confirming keyboard, and keypad inputs through touch. Surface profiling gives tactile feedback of the location of important keys. Displays are based on phosphors, liquid-crystals, light-emitting diodes and, most recently, light-emitting polymers. Surface printing techniques allow the application of icons, color coding, bar-coding, and text.

Communication is a desirable way in which products interact with people. Not all interactions are so desirable.

Noise Management

Sound is caused by vibration; its pitch depends on its frequency. The (youthful) human ear responds to frequencies from about 20 to about 20,000 HZ, corresponding to wavelengths of 17 m to 17 mm. The bottom note on a piano is 28 HZ, the top note 4186 HZ. The

4.10 How Loud Is Loud?

Sound levels in decibels.

Sound Source	dB
Threshold of hearing	0
Office background noise	50
Road traffic	80
Discotheque	100
Pneumatic drill at 1 m	110
Tet take-off at 100 m	120

4.11 Soaking up Sound

Sound-absorption coefficients.

Material	500–4000 Hz
Glazed tiles	0.01–0.02
Rough concrete	0.02–0.04
Wood	0.15–0.80
Cork tiles	0.20–0.55
Thick carpet	0.30–0.80
Expanded polystyrene	0.35–0.55
Acoustic spray plaster	0.50–0.60
Glass wool	0.50–0.99

most important range, from the point of view of acoustic design, is roughly 500–4000 Hz. Sound pressure is measured in Pascals (Pa), but because audible sound pressure has a range of about 10⁶ it is more convenient to use a logarithmic scale with units of decibels (dB). Figure 4.10 shows levels, measured in dB. Sound levels above 50 dB can impair concentration. Sustained sound levels above 90 dB cause damage to hearing.

Vibration, like noise, becomes damaging above a critical threshold. The level of vibration is characterized by the acceleration (units, m/sec²) associated with it; safe practice requires levels below 1 m/sec² (0.1 g where g is the acceleration due to gravity). The frequency, too, is important: less than 1 Hz gives sea-sickness; 1–100 Hz

gives breathing difficulties and headaches; 10–1000 Hz causes loss of sense of touch or “white finger”. Duration, too, is important – the longer the duration, the lower the level should be.

The mechanism for reducing sound and vibration levels within a given enclosed space (a room, for instance) depends on where it comes from. If it is generated within the room, one seeks to *absorb* the sound. If it comes from outside, one seeks to *insulate* the space to keep the sound out. And if it is transmitted through the frame of the structure itself (deriving from a machine tool, or from traffic), one seeks to *isolate* the structure from the source of vibration.

In product design it is usually necessary to absorb sound. Soft porous materials absorb incident, airborne sound waves, converting them into heat. (Sound power, even for a very loud noise, is small, so the temperature rise is negligible.) Porous or highly flexible materials such as low density polymer and ceramic foams, plaster, and fiber-glass absorb well; so do woven polymers like carpets and curtains. The proportion of sound-absorbed by a surface is called the “sound-absorption coefficient”. A material with a coefficient of 0.8 absorbs 80% of the sound that hits it, reflecting 20% back; one with a coefficient of 0.03, absorbs only 3% of the sound, reflecting 97%. Figure 4.11 shows sound-absorption coefficients for a number of materials.

Vibration is damped by isolating the source of vibration from the rest of the structure with high-damping rubber mounts, foams, elastomer grips, etc.

A composite of rubber filled with cork particles is a good choice here. The low shear modulus of the rubber isolates shear waves, and the compressibility of the cork adds a high impedance to compressive waves.

Thermal Management

All products that consume power generate heat, creating two classes of problems in thermal management. In the first, the challenge is to insulate parts that are sensitive to heat or that will be touched by the operator so that they don't get too hot: the hairdryer in which the casing must be insulated from the heating element. In the second, the challenge is the opposite one: that of transmitting or spreading heat, requiring materials that conduct: quality saucepans use high conducting materials to spread heat laterally for even cooking.

Polymers, with thermal conductivities, λ , around 0.25 W/mK, are good insulators. Still air ($\lambda = 0.025$) is much better; CO_2 ($\lambda = 0.016$) and CFCs such as trichlorofluoromethane, CCl_3F ($\lambda = 0.008$), are better still. The best insulating materials are foams that trap one of these gasses in closed pores, or fibrous materials like glass wool or mineral fiber that hold air still. If the temperature of the heat source is low ($<150^\circ\text{C}$) and strength is not required, polymer foams are a good choice. If the source temperature is high, glass wool or foam, mineral fibers and ceramic foams are a better choice. And if high strength is also needed, compacted mica or porous ceramic may be best.

When conduction is the aim, the best materials are solid silver, gold, or diamond (!) but these, for obvious

reasons, may not be viable choices. Solid copper and solid aluminum come close and are inexpensive and easy to shape: most heat-spreading systems use them. Occasionally, materials that conduct heat well but do not conduct electricity (they are electrical insulators) are required: here the best choice is aluminum nitride, AlN , or beryllia, BeO . Figure 4.12 lists the conductivities of representative conductors and insulators.

Light Management

Few products generate excessive light intensity, but many reflect light in ways that interfere with the vision of the operator. The reflectivity of a surface measures the fraction of the light intensity, incident at an angle of 60° to the surface, that is reflected back to an observer at 120° (that is, an equal angle on the other side). A black matte surface reflects less than 1%; a high gloss surface reflects 80% or more; a mirror reflects it all. Reflectivities are listed in 4.13.

The reflectivity of a surface depends on the material of which it is made or coated, and the smoothness of this surface: both color and texture are important. It is controlled by the use of low reflectivity coatings and light absorbing screens.

The Environment: “Green” Design and Sustainability

What have you discarded lately that still worked or, if it didn't, could have been fixed? Changing trends, pushed by seductive advertising, reinforce the

4.12 Managing Heat

Thermal conductivities of selected materials.

Material	W/m K
Copper	384
Aluminum	230
Glass	1.1
Solid polymers	0.15–0.35
Pine	0.112
Balsa	0.055
Cork	0.045
Glass foam	0.050
Mineral fiber	0.046
Glass wool	0.042
Polymer foams	0.02–0.10

4.13 Mirror or Matte?

Reflectivity of materials and surfaces.

Material	%
Aluminum	60
Beryllium	49
Carbon steel	57
Invar	41
Magnesium	72
Stainless steel	70
Titanium	56
Surface Texture %	
Dead matte	<1
Matte	1–10
Eggshell	15–20
Semi-gloss	40–50
Full gloss	>80
Mirror	>95

desire for the new and urge the replacement of still-useful objects. Industrial design carries a heavy responsibility here – it has, at certain periods, been directed toward creative obsolescence: designing products that are desirable only if new, and urging the consumer to buy the latest models, using marketing techniques that imply that acquiring them is a social and psychological necessity. And – as we said in Chapter 2 – this accelerating consumption creates problems that are an increasing source of concern.

But that is only half the picture. A well-designed product can outlive its design life by centuries, and – far from becoming unwanted – can acquire value with age. The auction houses and antique dealers of New York, London, and Paris thrive on the sale of products that, often, were designed for practical purposes but are now valued more highly for their aesthetics, associations, and perceived qualities. People do not throw away products for which they feel emotional attachment. So there you have it: industrial design both as villain and as hero. Let us look into this in a bit more detail because it is a complex maze, with the potential for many wrong turns.

Materials as Resources

Will we really run out of materials or of oil and gas? The present prodigal use suggests that we might; reports have been written, starting with the famous Club of Rome report⁹ in 1972, suggesting that we will. A market economy may have many faults, but it also contains feedback mechanisms of a restrain-

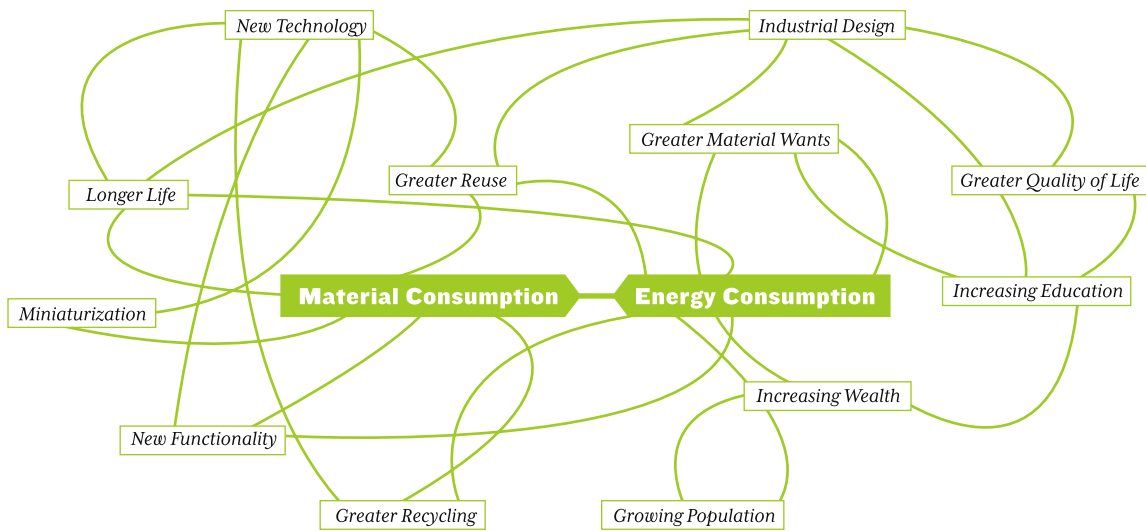
ing nature. As the natural resources of materials are consumed and ore-grades diminish, prices rise; the lower-grade uses become economically untenable and consumption falls. A more balanced view is that we will never “run out” of anything, but that the adjustments imposed by rising cost may be very uncomfortable to live with, giving sufficient reason to urge a policy of restraint and conservation.

A more immediate concern is the impact of manufacturing on the environment. As already mentioned in Chapter 2, there are those who, observing the present level of consumption and the rate of its growth, argue that only a massive reduction can reduce the impact on the environment to an acceptable level. Can such changes be achieved without a change in lifestyle that few could accept? They might, though it is far from certain. Take the example of the automobile. Twenty-five years ago the average car did 20 miles per gallon (14 liters/100 km); today you can buy a family car that does 60 mpg (4.7 liters/100 km) – a factor of 3. The average life of a tire, 25 years ago, was about 20,000 miles; now it is nearer 50,000 – a factor of 2.5. So large changes are possible, but they are not enough. Car ownership and the average distance driven per year have both increased over the same period by a factor of roughly 6, far outweighing even these massive changes.

Balancing Material and Energy Consumption

The most obvious ways to conserve material are to make products smaller,

9. “*The Limits to Growth – 1st Report of the Club of Rome*,” by Meadows et al. (1972), provoked a strong reaction when first published, but proved, in some ways, to be visionary.



make them last longer and recycle them when they finally reach the end of their lives. But the seemingly obvious can sometimes be deceptive. Materials and energy form part of a complex and highly interactive system, sketched in 4.14. Here primary catalysts of consumption, such as population growth, increasing wealth, and new technology, appear to accelerate the consumption of materials and energy and the by-products that these produce. But – to take just one example – wealth also brings education, and with it, greater awareness of the problems these by-products create, restraining consumption.

The influences have complex interactions. New technology, as an example, offers more material and energy-efficient products, yet by also offering new functionality it creates obsolescence and the desire to replace a product that has

useful life left in it. Electronic products are prime examples of this: 80% are discarded while still functional. And observe, even at this simple level, the consequences of longer product life – a seemingly obvious measure. It can certainly help to conserve materials but, in an era in which new technology delivers cleaner, leaner products (particularly true of cars, electronics, and household appliances), extending the life of old products can have a negative influence on the environment. And as a final example, consider the bivalent influence of industrial design. The lasting designs of the past are evidence of its ability to create products that are treasured and conserved. But today it is frequently used as a potent tool to stimulate consumption, creating the perception that “new” is desirable and that even slightly “old” is unappealing. How can design be used to

4.14 A Complicated Interaction with the Environment

The interactive nature of the influences on consumption of materials and energy.

support and enhance the environment, rather than threatening it?

Eco-Design

When your house no longer suits you, you have two choices: you can buy a new house or you can adapt the one you have got, and in adapting it you make it more personally yours. Houses allow this. Most other products do not; and an old product (unlike an old house) is often perceived to have such low value that it is simply discarded. And that highlights a design challenge: to create products that can be adapted and personalized so that they acquire, like a house, a character of their own, and transmit the message “keep me, I’m part of your life.” This suggests a union of technical and industrial design to create products that can accommodate evolving technology but at the same time are made with a quality of material, design and adaptability that creates lasting and individual character, something to pass on to your children.

Well, that is perhaps an ideal¹⁰, one that relies as much on cultural change as on design. To address the problem at a more practical level and to identify more clearly the role of materials, it is necessary to recognize two key features. The first is the point made by 4.14: the

consumption of materials and energy is part of a highly complex and interactive system. Simple solutions (“ban the use of lead,” “don’t use plastics because they are energy-intensive”) can have the opposite of the desired effect. The second follows from the concept of the material’s lifecycle shown in 2.3. The point is that there are four significant stages. Ore and feedstock are consumed to create materials; these are manufactured into products that, almost always, consume energy throughout their lives; and these, at life’s end, are discarded or recycled. Passive products are those that do not require much energy to meet their primary function (furniture, carpets, and fittings, bridges, unheated buildings); for these, the material production and manufacture phases dominate the consumption of energy and materials (4.15). Here extending product life makes good sense; doubling the life of any one of them almost halves resource consumption. We have already seen that well-designed furniture, made from quality materials, can acquire value and desirability with time, and its unlimited life has no negative consequences in the system of 4.14.

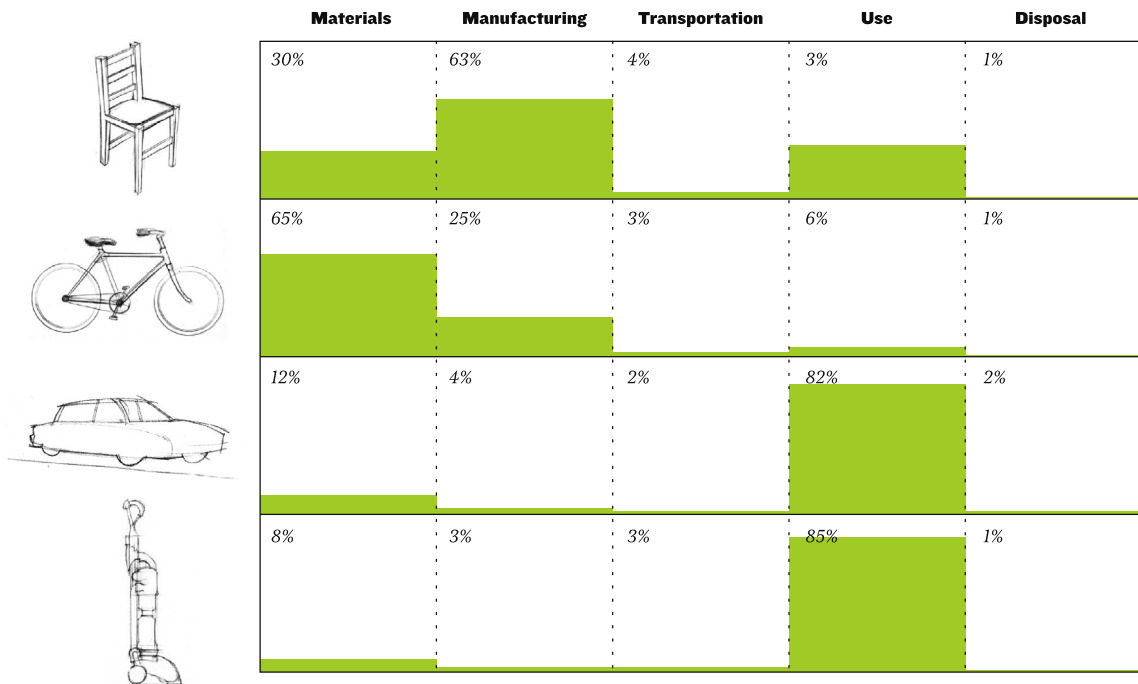
By contrast, energy-consuming products (household appliances, vehicles, heated, or cooled buildings) consume more resources – above all, more energy – in the use phase of their life than in all the others put together (4.16). The greatest potential for improvement then lies in examining use and disposal rather than manufacture. Extending the life of energy-consuming products, particularly those in which technology is changing

10. For an organization with such an ideal, see www.etrnally-yours.nl.

4.15 The Ecoplanter

This planter, designed for the small apartment, is made of recyclable polypropylene and composts the packaging in which it was delivered (Image courtesy of Cynthia Garden Design).





rapidly, may be counterproductive, for reasons already given. Instead, the focus is on lightweight materials to reduce fuel consumption in transport systems, more efficient electronics with stand-by or “sleep” modes to cut power consumption when the product is inactive, and materials with better thermal insulation to reduce energy loss in refrigerators, freezers, and heating systems. And if product life is short, re-use or recycling offers particularly large gains.

National Legislation: Standards, Directives, Taxes, Trading

Legislation, typified by the acts of the US Environmental Agency or the Environmental Directives of the

European Union, exerts pressure on manufacturers to assess the environmental impact of their products and take steps to minimize it. Legislation takes four broad forms:

- Setting up standards;
- Negotiating voluntary agreements with industry;
- Enacting binding legislation that imposes requirements with penalties if they are not met;
- Establishing economic instruments that seek to use market forces to induce change; these take the form of taxes, subsidies, and trading schemes.

4.16 Energy in Products

Approximate values for the energy consumed in production, manufacture, use, and disposal of four classes of products.

Industry Standards

ISO 14000 of the International Standards Organization defines a family of standards for environmental management systems¹¹. It contains the set ISO 14040, 14041, 14042, and 14043 published between 1997 and 2000, prescribing broad but vague procedures for life-cycle assessment and its interpretation. ISO 14025 is a further standard guiding the reporting of LCA data as an Environmental Product Declaration (EPD) or a Climate Declaration (CD).¹²

Voluntary agreements and binding legislation. Current legislation is aimed at internalizing costs¹³ and conserving materials by increasing manufacturers' responsibilities, placing on them the burden of cost for environmental damage and disposal. Here are some examples.

- The US Resource Conservation and Recovery Act (RCRA) is a Federal law that aims to protect the public from harm caused by waste disposal, and encourage reuse, reduction, and recycling.
- The US EPA Code of Federal Regulation (CFR) Protection of the Environment (CFR Part 302) deals with protection of the environment and human health, imposing restrictions on chemicals released into the environment during manufacture, life, and disposal.
- The European Volatile Organic Compounds (VOCs, 1999) Directive limits the emissions of VOCs from organic solvents and carriers like

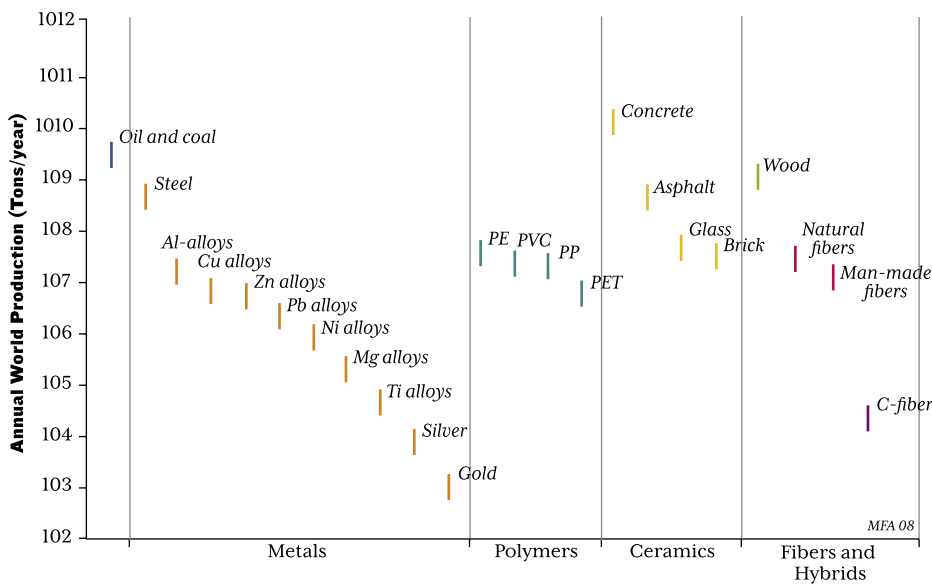
those in organic-based paints and industrial cleaning fluids. Compliance became mandatory in 2007.

- The European End-of-Life Vehicles (ELV, 2000) Directive establishes norms for recovering materials from used cars. The initial target, a rate of reuse and recycling of 80% by weight of the vehicle and the safe disposal of hazardous materials, was established in 2006. By 2015 the recycling target rises to 85%.
- The European Waste Electrical and Electronic Equipment (WEEE, 2002) Directive seeks to increase recovery, recycling, and reuse of electronic equipment and electrical appliances. It requires that producers finance the collection, recovery, and safe disposal of their products and meet certain recycling targets.
- The European Energy-using Products (EuP, 2003) Directive establishes a framework of eco-design requirements for products that use energy – appliances, electronic equipment, pumps, motors, and the like. It requires that manufacturers of any product that uses energy “shall demonstrate that they have considered the use of energy in their product as it relates to materials, manufacture, packaging, transport and distribution, use, and end of life. For each of these the consumption of energy must be assessed and steps to minimise it identified”.

11. See www.iso-14001.org.uk/iso-14040 for a summary.

12. For the more intimate details, see www.environdec.com.

13. The “polluter pays” principle.



4.17 Raw Materials

The world production of the materials that we use in the largest quantities.

- The European Registration, Evaluation, Authorization and Restriction of Chemical Substances (REACH, 2006) Directive places responsibility on manufacturers to manage risks from chemicals and to find substitutes for those that are most damaging. Manufacturers in Europe and importers into Europe must register the restricted substances they use as a technical dossiers for each, listing their properties, an assessment of their impacts on the environment and human health, and the risk-reduction measures they have adopted. Without registration, it is illegal for manufacturers and importers to place the substances on the market.

The burden this legislation places on the materials and manufacturing industries is considerable. All impose additional cost on manufacturers. These can be mini-

mized by the use of well-designed software tools. A survey of these, and a deeper discussion of environmental legislation can be found in a number of recent books¹⁴.

Embodied energy

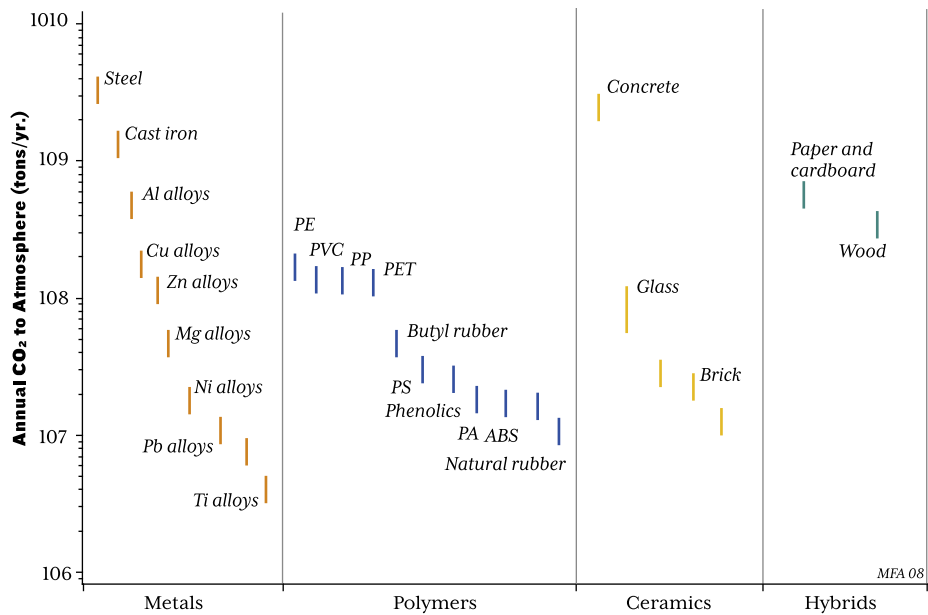
About 20% of all the energy we consume of the CO₂ we release into the atmosphere arises from making the materials of manufacture (4.17, 4.18). Most energy comes from making the 11 we use in the largest quantities. The embodied energy is the energy that must be committed to create 1 kg of usable material – 1 kg of steel stock, or of PET pellets, or of cement powder, for example – measured in MJ/kg¹⁵. It includes the energy to mine, transport, and refine the ores and feedstock required to make the material, and it includes the energy to convert the refined ore to metal or the oil-derived chemicals to plastics. The term “embodied energy” is misleading in that it

14. See Guidice et al (2006), Vezzoli and Manzini (2008) and Ashby (2009). 1 MJ (mega joule) is about 0.3 kWh.

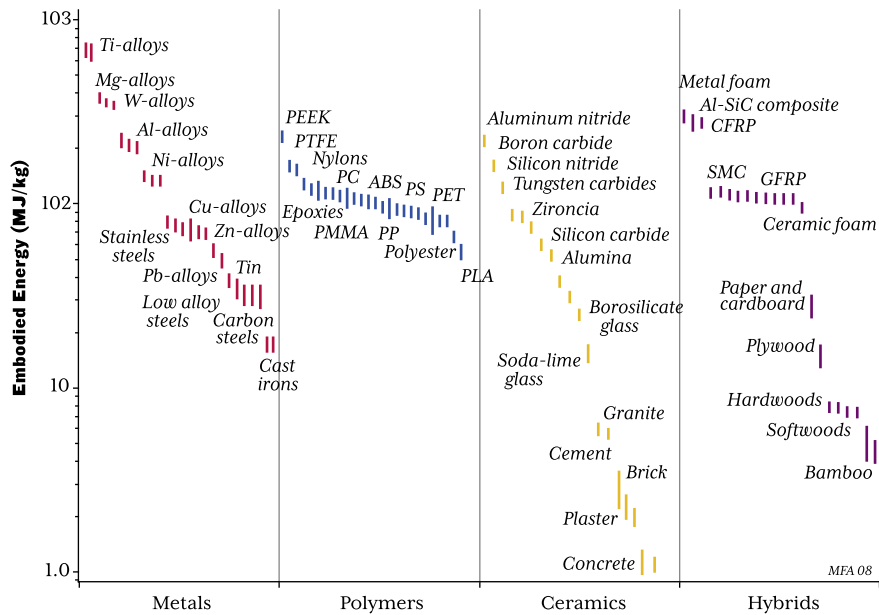
15. Embodied energies are, typically, about 100 MJ/kg- that is roughly the energy contained in 3 liters or 1 US gallon of gasoline.

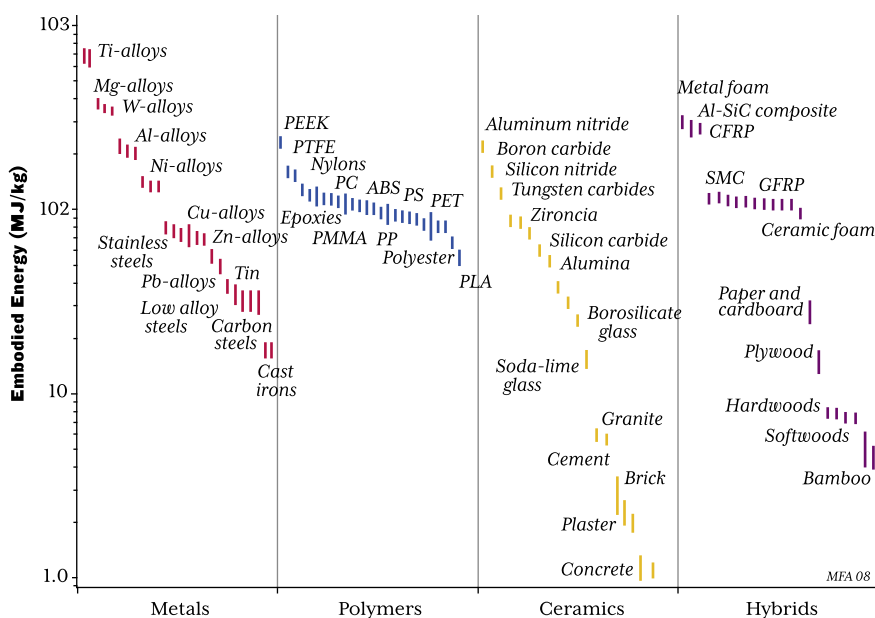
4.18 CO₂ Levels

The carbon dioxide released into the atmosphere as a consequence of making the 11 materials enclosed in the broken box.



4.19 Embodied energies of materials per unit mass





suggests that this energy is somehow contained within the material and so could be recovered. Some is – that is why recycling is attractive – but by no means all.

Embodied energies per unit mass (units: MJ/kg) are compared in 4.19. Among common metals, the light alloys based on aluminum, magnesium, and titanium have the highest values, approaching 1000 MJ/kg for titanium (precious metals lie still higher). Polymers all cluster around 100 MJ/kg, less than the light alloys, but considerably more than steels and cast irons, with energies between 20 and 40 MJ/kg. Technical ceramics such as electronic-grade alumina (Al_2O_3) have high energies; those for glass, cement, brick, and concrete are much lower. Composites, too, have a wide spread.

High performance composites – here we think of CFRP (carbon fiber-reinforced polymers) – lie at the top, well above most metals. At the other extreme paper, plywood, and timber are comparable with the other materials of the construction industry.

But is embodied energy per unit mass the proper basis of comparison? Suppose, instead, the comparison is made per unit volume (4.20). The picture changes. Now metals as a family lie above the others. Polymers cluster around a value that is lower than most metals – they are not, by this measure, the energy-hungry materials they are sometimes made out to be. The non-metallic materials of construction – concrete, brick, wood – lie far below all of them. CFRP is now comparable with aluminum.

4.21 Reaching the Senses

The tactile, visual, acoustic attributes of materials

Sense	Attribute
Touch	Warm
	Cold
	Soft
	Hard
	Flexible
	Stiff
Sight	Optically clear
	Transparent
	Translucent
	Opaque
	Reflective
	Glossy
	Matte
	Textured
Hearing	Muffled
	Dull
	Sharp
	Resonant
	Ringing
	Low pitched
	High pitched
Taste/Smell	Bitter
	Sweet

This raises an obvious question: if we are to choose materials to minimize embodied energy, what basis of comparison should we use? A mistaken choice invalidates the comparison, as we have just seen. The right answer is to compare energy per unit of function.

Aesthetics: The Five Senses

Aesthetic attributes are those that relate to the senses: sight, touch, sound, smell, and taste (4.21). We will focus on the first three in this chapter, although it can certainly be equally necessary and inspiring to consider the last two – smell and taste. Almost everyone would agree that metals feel “cold”; that cork feels “warm”; that a wine glass, when struck, “rings”; that a pewter mug sounds “dull”, even “dead”. From a distance, a plastic drinking glass can be visually indistinguishable from one made of glass, but pick it up and it feels lighter, warmer, less rigid; and tap it and it sounds quite different. The impression it leaves is so different from glass that, in an expensive restaurant, it would be completely unacceptable. These are the simplest of aesthetic distinctions, and, in an approximate way, they can be quantified. There are obvious limitations here, but within these it is worth a try, since it could allow a first-level screening of materials to meet specified aesthetic requirements. So here goes.

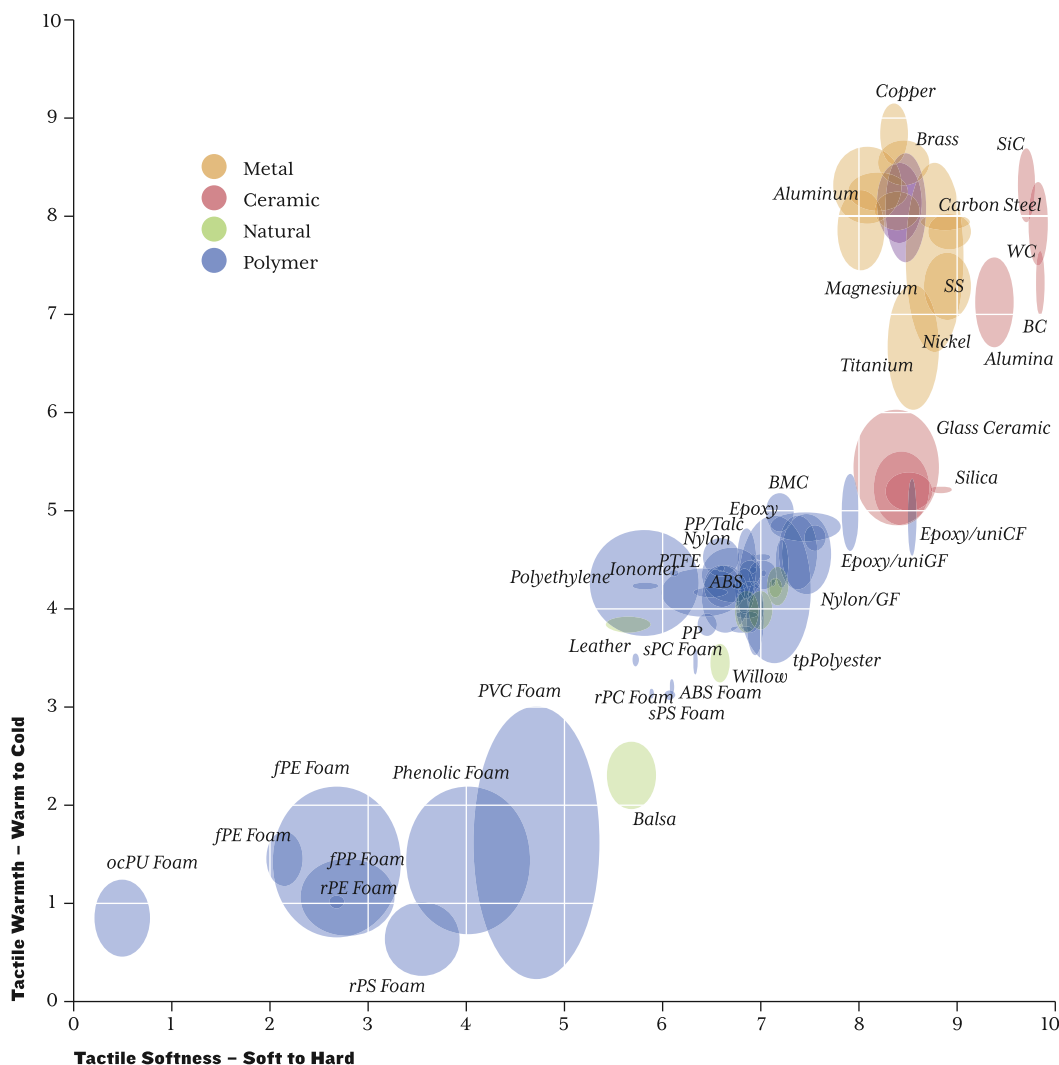
Touch: the Tactile Attributes

Steel is “hard”; so is glass; diamond is harder than either of them. Hard materials do not scratch easily; indeed they can be used to scratch other materials.

They generally accept the high polish, resist distortion, and are durable. The impression that a material is hard is directly related to the material property “Hardness,” measured by materials engineers and tabulated in handbooks. Here is an example of a sensory attribute that relates directly to a technical one.

“Soft” sounds like the opposite of “hard” but, in engineering terms, it is not – there is no engineering property called “softness”. A soft material deflects when handled, it gives a little, it is squashy, but when it is released it returns to its original shape. This is elastic (or viscoelastic) behavior, and the material property that has the most influence on it is the modulus, not the hardness. Elastomers (rubbers) feel soft; so do polymer foams: both classes of material have moduli that are 100 to 10,000 lower than ordinary “hard” solids; it is this that makes them feel soft. Hard materials can be made “soft” by forming them into shapes in which they bend or twist: hard steels shaped into soft springs; glass drawn into fibers and woven into cloth. To compare the intrinsic softness of materials (as opposed to the softness acquired by shape) materials must be compared in the same shape, and then it is the modulus that is the key property. An appropriate measure of hardness and softness is discussed in the Appendix of this chapter. It is used as one axis of 4.22.

A material feels “cold” to the touch if it conducts heat away from the finger quickly; it is “warm” if it does not. This has something to do with the technical attribute “thermal conductivity” but there is more to it than that – it depends also on specific heat. A measure of the perceived coldness or warmth of



a material (in the sense of heat, not of color) is developed in the Appendix. It is shown as the other axis of 4.22. The figure nicely displays the tactile properties of materials. Polymer foams and low density woods are warm and soft; so are balsa and cork. Ceramics, stone, and metals are cold and hard; so is glass. Polymers and composites lie in between.

Sight: the Visual Attributes

Metals are opaque. Most ceramics, because they are polycrystalline and the crystals scatter light, are either opaque or translucent. Glasses, and single crystals of some ceramics, are transparent. Polymers have the greatest diversity of transparency, ranging from transparency of optical quality to completely opaque. Transparency is commonly

4.22 The Tactile Attributes of Materials

Some materials feel soft and warm; others, hard and cold. Here these attributes are charted, revealing a striking correlation between the two (CES Edu, 2009).

16. Pantone (www.pantone.com.) provide detailed advice on color selection, including color-matching charts and good descriptions of the associations and perceptions of color.

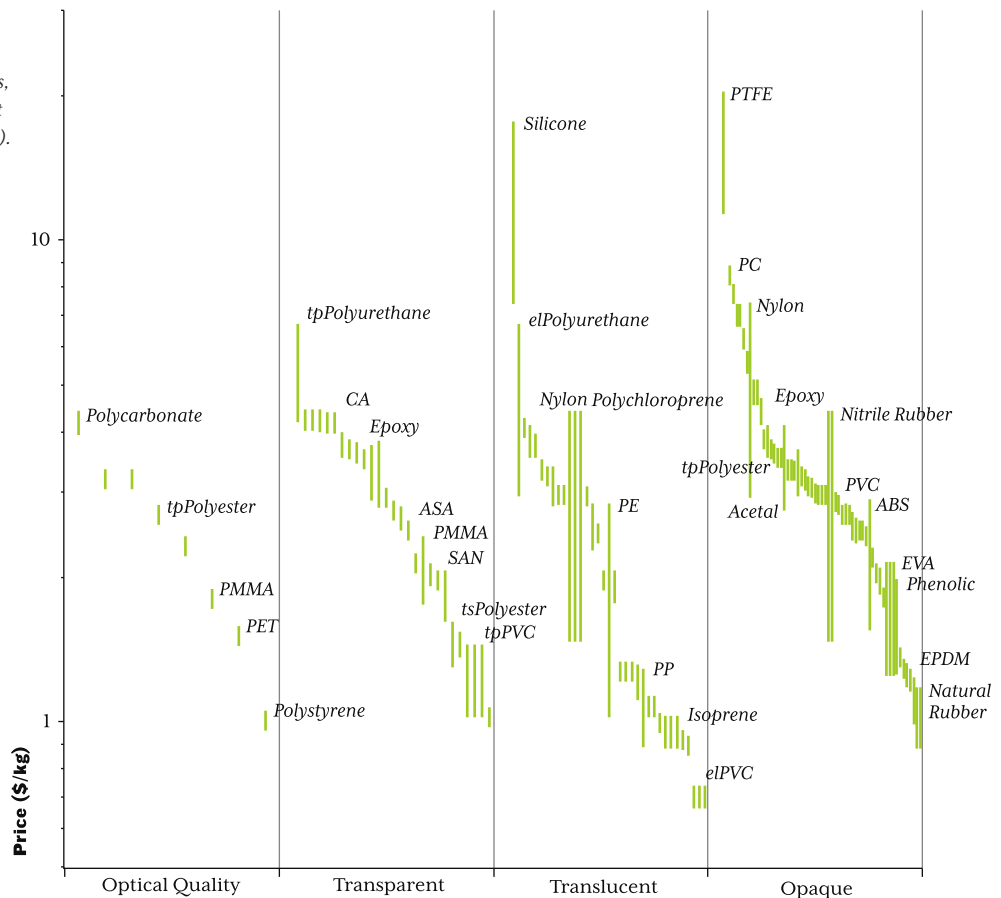
described by a four-level ranking: opaque, translucent, transparent, and water-clear or optical quality. These everyday words are easily understood; they are used in the materials profiles later in this book. Figure 4.23 ranks the transparency of common polymers. In order to spread the data in a useful way, it is plotted against cost. The cheapest polymers offering optical transparency are PET, PS, and PMMA. Epoxies can be transparent but not with optical quality. Nylons are, at best, translucent. Phenolics, most ABS and all carbon-filled

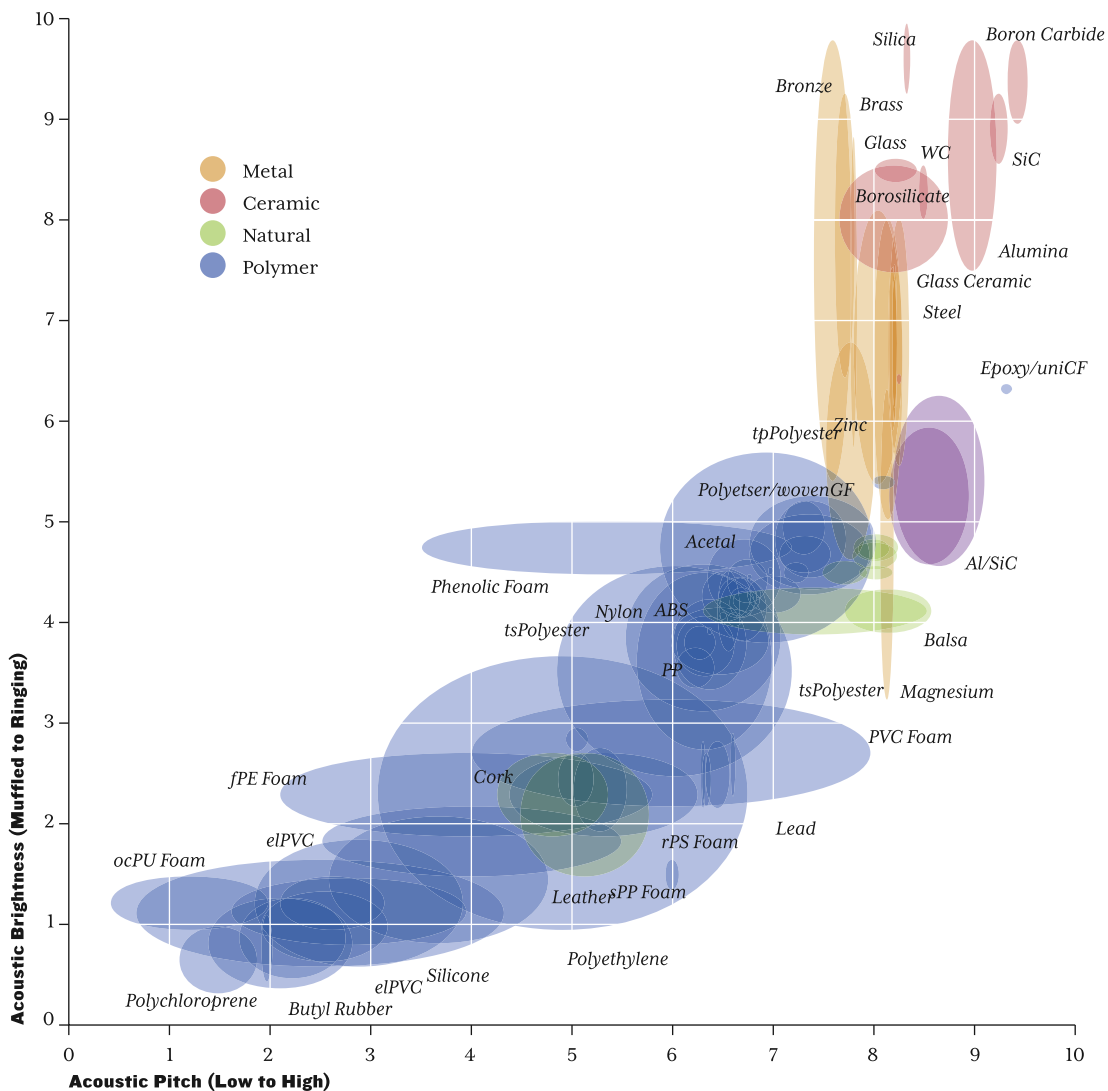
or reinforced polymers are translucent or opaque.

Color can be quantified by analyzing spectra but this – from a design standpoint – doesn't help much. A more effective method is one of color matching, using color charts such as those provided by Pantone¹⁶; once a match is found it can be described by the code that each color carries. Finally, there is reflectivity, an attribute that depends partly on material and partly on surface detail. Like transparency, it is commonly described by a ranking: dead

4.23 Price and Light Transmission

The optical attributes of polymers, shown in order of decreasing cost in each category (CES Edu, 2009).





matte, eggshell, semigloss, gloss, mirror
(4.13).

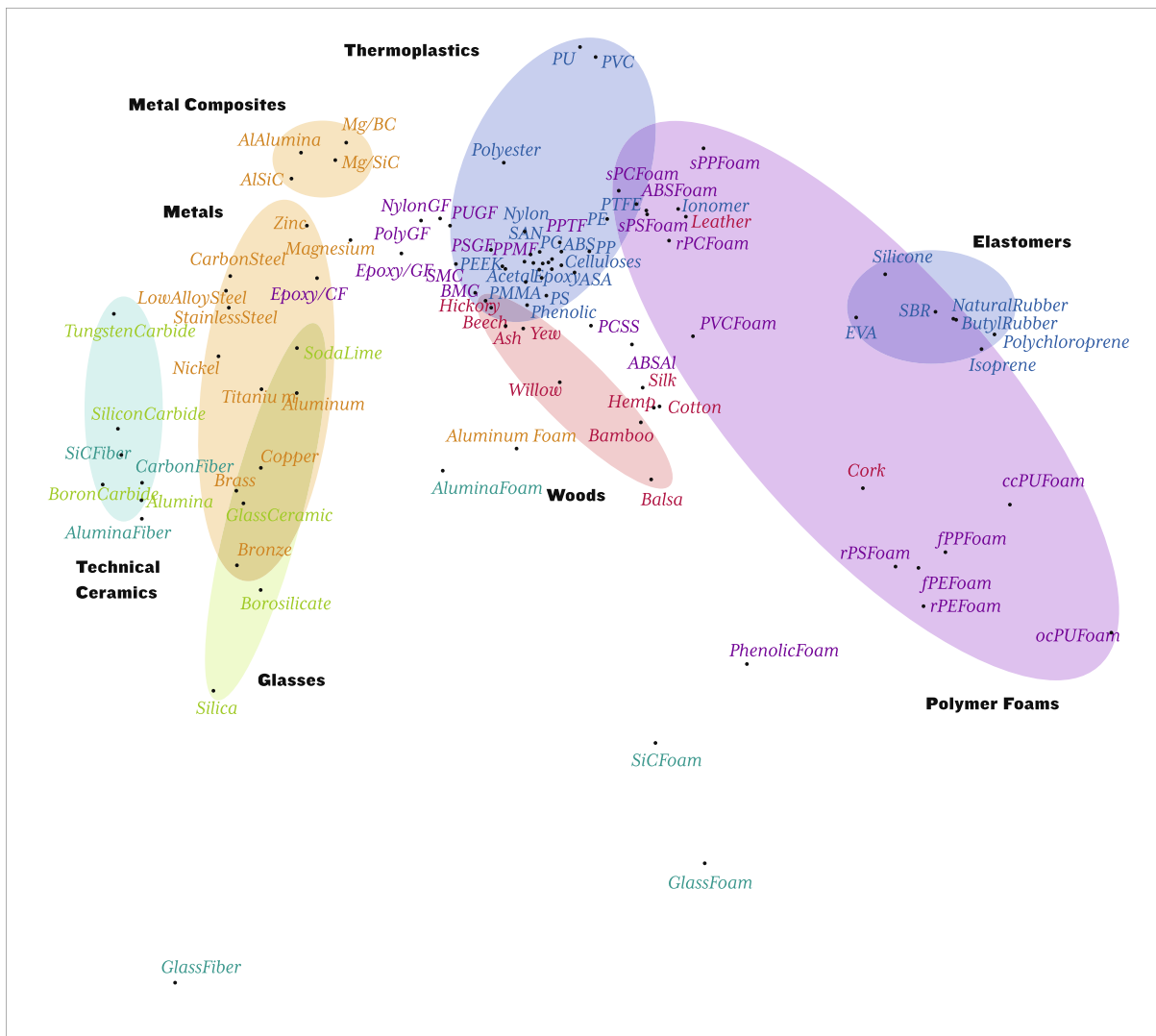
Sound: the Acoustic Attributes

The frequency of sound (pitch) emitted when an object is struck relates to two material properties: modulus and density. A measure of this pitch, detailed in the Appendix, is used as one axis of

4.24. Frequency is not the only aspect of acoustic response – another has to do with damping. A highly damped material sounds dull and muffled; one with low damping rings. Acoustic brightness – the inverse of damping (the Appendix again) – is used as the other axis of 4.24. It groups materials that have similar acoustic behavior.

4.24 Pitch and Brightness

The acoustic attributes of materials (CES Edu, 2009).



4.25 Multi-Dimensional Maps: Aesthetic Attributes

An MDS map of materials by aesthetic attributes (Data from CES Edu, 2009).

Bronze, glass, and steel ring when struck, and the sound they emit has – on a relative scale – a high pitch; they are used to make bells; alumina, on this ranking, has the same bell-like qualities. Rubber, foams, and many polymers sound dull, and, relative to metals, they vibrate at low frequencies; they are used for sound damping. Lead, too, is dull and

low pitched; it is used to clad buildings for sound insulation.

What happens if all these are combined? [Figure 4.25](#) shows the result. It is an MDS map combining the attributes we have just described. As with the earlier MDS map, there is pronounced clustering of a kind that is broadly consistent with experience – leather is near PVC, ceram-

ics near metals, woods near phenolics. The map should not be overinterpreted, for the reasons given already; but it does have the power of suggestion.

Personality: Building Emotional Connections

We interact with materials through products. The interaction involves their technical and aesthetic attributes, but these are not all. A product has perceived attributes and associations – it is these, in part, that give it its personality, something designers work hard to create. But can a *material* be said to have perceived attributes or indisputable associations? A personality? At first sight, no – it acquires these only when used in a product. Like an actor, it can assume many different personalities, depending on the role it is asked to play.

And yet...think of wood. It is a natural material with a grain that gives a surface texture, pattern, and feel that other materials do not have. It is tactile – it is perceived as warmer than many other materials, and seemingly softer. It is associated with characteristic sounds and smells. It has a tradition; it carries associations of craftsmanship. And it ages well, acquiring additional character with time. Things made of wood are valued more highly when they are old than when they are new. There is more to this than just aesthetics; there are the makings of a personality, to be brought out by the designer, certainly, but there nonetheless.

And metals... Metals seem cold, clean, precise. They ring when struck. They

can reflect – particularly when polished. They are accepted and trusted: machined metal looks strong, its very nature suggests it has been engineered. The strength of metals allows slender structures – the cathedral-like space of railway stations or the span of bridges. It can be worked into flowing forms like intricate lace or cast into solid shapes with integral detail and complexity. And – like wood – metals can age well, acquiring a patina that makes them more attractive than when newly polished – think of the bronze of sculptures, the pewter of mugs, the lead and copper of roofs.

And ceramics or glass? They have a long tradition: think of Greek pottery and Roman glass. They accept almost any color; this and their total resistance to scratching, abrasion, discoloration, and corrosion gives them a certain immortality, threatened only by their brittleness. They are – or were – the materials of great craft-based industries: Venetian glass, Meissen porcelain, Wedgwood pottery, valued, sometimes, as highly as silver. And ceramic today has an additional association – that of advanced technology: kitchen stove-tops, high pressure/high temperature valves, space shuttle tiles... materials for extreme conditions.

And, finally, polymers. “A cheap, plastic imitation” used to be a common phrase – and that is a hard reputation to live down. It derives from an early use of plastics: to simulate the color and gloss of Japanese handmade pottery, much valued in Europe. Commodity polymers *are* cheap. They are easily colored and molded (that is why they are called “plastic”), making imitation easy. Unlike

4.26 Perceptions

The perceived attributes of materials or products, listed as pairs of opposites.

17. There are a number of such studies. They make fascinating reading. [Manzini \(1989\)](#) illustrates how the combination of material and form is used to obtain specific product attributes and human responses. Harni (1996) explores the sensory experiences and associations of objects using, as prototypes, 12 different styles: folklore, deluxe, kitsch, porno, toy, cartoon, sport, pseudo-eco, army, professional, space, and “white,” each applied to five products: a toaster, an iron, a hairdryer, a kitchen mixer, and an electric shaver. The work demonstrates dramatically the way in which materials, surface treatments, and forms can be used to create perceived attributes. At a more formal level there is the field of product semiotics – the study of signs and their role in socio-cultural behavior. A product transmits signs that are interpreted differently depending on the observer and the context. The terms “icon”, “index”, and “symbol” are used as a basic vocabulary in describing product semiotics. An icon is prototype, an idealized abstraction of the attributes of a product (a frame representing a painting), an index is connected to what it signifies by cause (tracks in the snow indicate that someone was here), and a symbol represents a recognition of agreement between people (a crown indicates royalty). These can be used to build meaning into products.

Perceived Attributes of Materials or Products		
Aggressive	.	Passive
Cheap	.	Expensive
Classic	.	Trendy
Clinical	.	Friendly
Clever	.	Silly
Common	.	Exclusive
Decorated	.	Plain
Delicate	.	Rugged
Disposable	.	Lasting
Dull	.	Sexy
Elegant	.	Clumsy
Extravagant	.	Restrained
Feminine	.	Masculine
Formal	.	Informal
Hand-made	.	Mass-produced
Honest	.	Deceptive
Humorous	.	Serious
Informal	.	Formal
Irritating	.	Loveable
Lasting	.	Disposable
Mature	.	Youthful
Nostalgic	.	Futuristic

ceramics, their gloss is easily scratched, and their colors fade – they do not age gracefully. You can see where the reputation came from. But is it justified? No other class of material can take on as many characters as polymers: colored, they look like ceramics; printed, they can look like wood or textile; metalized, they look exactly like metal. They can be as transparent as glass or as opaque as lead, as flexible as rubber or as stiff – when reinforced – as aluminum. But despite this chameleon-like behavior they do have a certain personality: they feel warm – much warmer than metal

or glass; they are adaptable – that is part of their special character; and they lend themselves, particularly, to brightly-colored, light-hearted, even humorous (e.g. comical, funny = humorous; durable, long-wearing = lasting), design.

So there is a character hidden in a material even before it has been made into an recognizable form – a sort of embedded personality, a shy one, not always visible, easily concealed or disguised, but one that, when appropriately manipulated, can contribute to good design. The attributes we discuss here are qualitative, sometimes subjective – a far remove from the sharp precision of technical attributes with which this chapter started. But – given their importance in product design – it is worth exploring them further. And here we must digress for a moment, turning from materials to products, to explore the easier question: how can the perceived attributes of products be characterized? We need a language – a way of expressing these things in words.

A Vocabulary of Perception

Research exists that explores the aesthetics and perceived attributes of products.¹⁷ These suggest that agreement can, to some degree, be reached in describing perceptions. Attempting to put words to perceived attributes is, of course, a risky business – not everyone sees them in the same way. They are subjective; they depend on the product itself, and, importantly, on the context and the culture in which it is used. They are sometimes ambiguous, and their meaning changes with time: a product that appears aggressive or luxurious today

can seem humorously retro or just plain ugly tomorrow (think of car styling). But we are bound by language – it is the most important way in which we communicate. So it is worth a try.

One way to assemble a vocabulary for perceptions is to do what any linguist, studying a new language, would do – listen to the words that native speakers use and observe the objects about which they are speaking. Newspapers, magazines, exhibition catalogs, and design books carry product reviews.¹⁸ They include pictures of the product, a profile of the designer, and, typically, a statement by the critic – the “native speaker” – of his or her perceptions of the product. A survey of these leads to the list in 4.26 – words used regularly to describe products and their attributes – each shown with an opposite to sharpen the meaning. The list has been simplified and reduced in length by replacing near-equivalent words with a single word (e.g. comical, funny = humorous; durable, long-wearing = lasting).

How useful is such a vocabulary? The critics use it to communicate with their readers, and given the popularity of the publications, they clearly speak a language that carries meaning for them. But is it one that non-experts can use? Experiments in which test groups are asked to assign words from the list to products that they are given (and can handle) show that, at least within a given socio-cultural group, agreement is, in a statistical sense, significant – about 80% of the group assign one or more of the same words to the same product. The motive of such studies is one of under-

standing perception and communicating it – the ability to attach words from the perceptions list of 4.22 (or some expansion of it) to products, so that those with similar perceived attributes can be compared. It is a useful idea and one to which we return in Chapter 7.

And – just in case this idea of perceptions still seems intellectually dubious – think of historical design styles (4.27). Describing a product as having elements of “Art Nouveau,” or “Streamform” or “Pop” conveys, in a single word or phrase, a cluster of ideas, some concrete, some abstract. Each style is associated with certain materials – Art Nouveau with carved wood, cast bronze, and wrought iron; Streamform with steel and aluminum; Pop with plastics. Each carries associations of form, decoration, and coloring. But above all is the association with an era – Art Nouveau with late 19th Century Europe, Streamform with the US in the 1930s, and Pop with the US in the 1950s – and with the cultural, economic, and intellectual character of that era – with its *personality*.

Thus a vocabulary to describe the perceived attributes of products is possible. If the words are put in context with images to illustrate them, they give a channel of communication – one that is useful in design, and often used (and misused) in advertising. As with any language the words and their meanings evolve with time. The difference here is that the rate of evolution is faster than in language as a whole, requiring regular rewriting of the lexicon. Like all words, these do not have universal meaning – but this we have to live with.

18. Examples are the *ID Magazine*, the “*International Design Year Book*” (1998,1999), the “*ID Magazine Annual Design Review*” (1998,1999), the books by Byars (1995, 1997a, b, 1998), and the catalogs of the MOMA exhibition called “*Mutant Materials*” (Antonelli, 1995) and that mounted by Connexion called “*Materials and Ideas for the Future*” (Arredo, 2000).

4.27 Design Styles

A chronology of selected movements in design, sometimes linked to material innovations.

1900 and Before

Art Nouveau	1890
Arts and Crafts	1890
Functional	1900

1900 to 1950

Modernist	1900
Futurist	1910
Art Deco	1920
Streamform	1930
Contemporary	1945

1950 and After

Pop	1960
Retro	1960
Classic	1970
Post-Modernist	1970
Memphis	1980

4.28 Abrasion Resistance and Weight

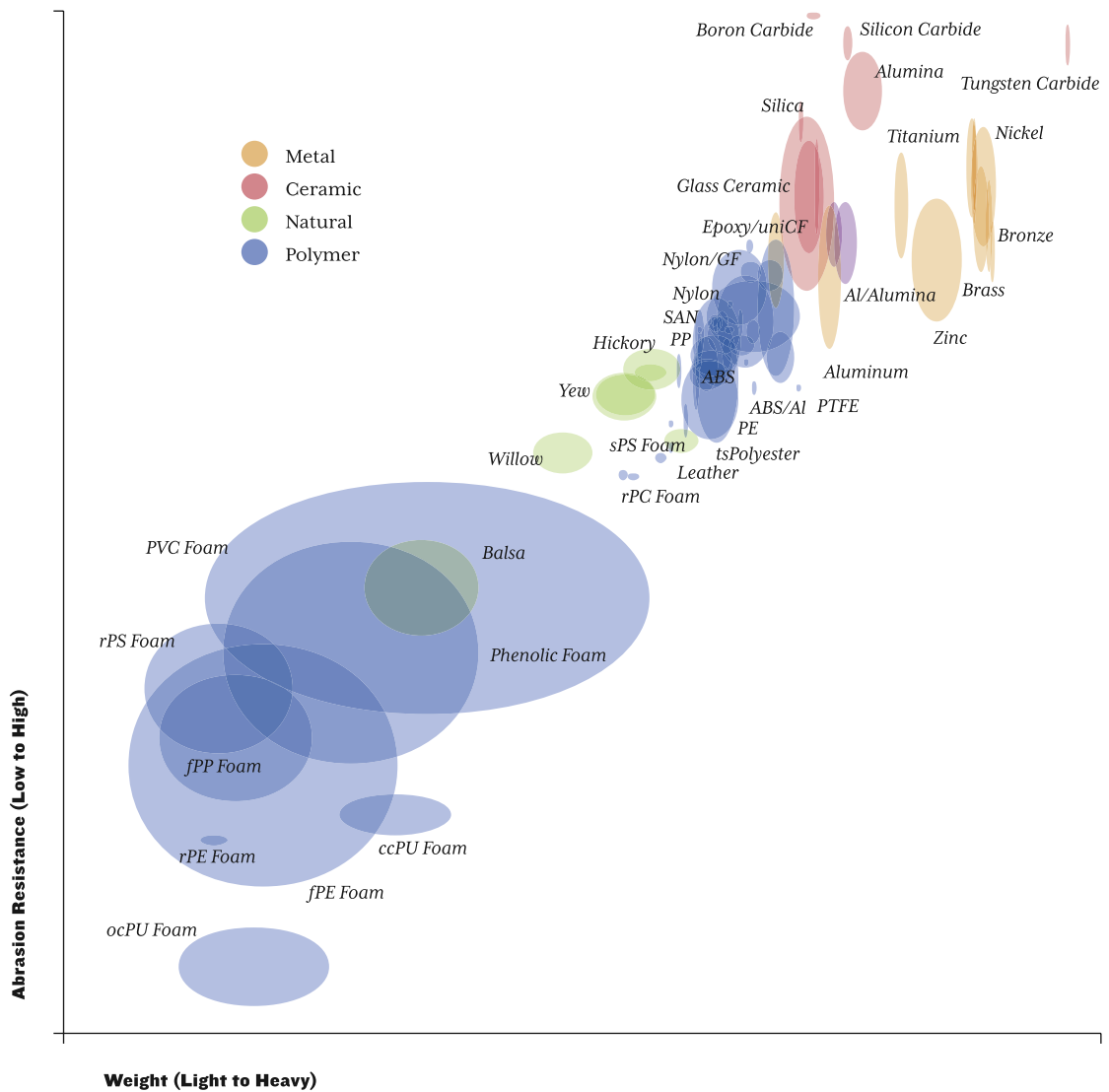
Materials with high hardness resist abrasion; those with high density are heavy. There is a strong correlation between the two (CES Edu, 2013).

The alternative is no communication at all.

So products have perceived attributes, and they can be associated with a certain style, and people can love the object itself, the experience it enables, and the story it tells. But can the same be said of materials?

Perception of Technical Attributes

You don't need a degree in engineering to know that some materials are tougher than others (some foods, too); some more resilient (some people, too); some more flexible (like your savings account); some less abrasion resistant (like children). These words – tough,



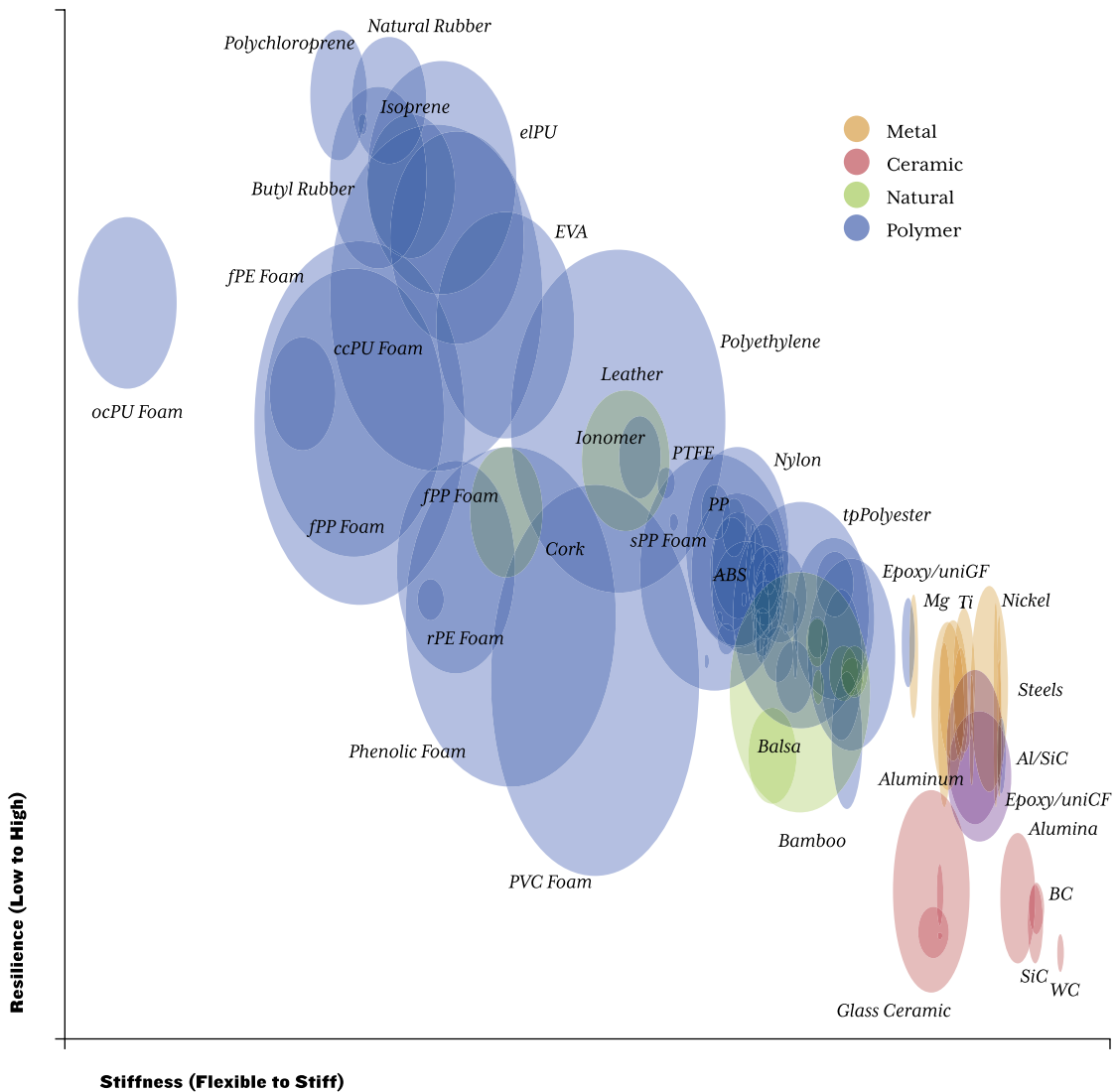
resilient, flexible, abrasion resistant – are words of everyday life deployed to describe the features of a material. These are perceptions of technical behavior, to be sure, and in this sense different from those of the list of 4.22. And because they are often based on technical attributes, they can, to some

degree, be quantified or measured, allowing materials to be ranked by these familiar terms.

For a given shape, the mass of an object depends on the density, ρ , of the material of which it is made. Abrasion resistance is more complex – its closest link is that to hardness, H . These two

4.29 Resilience and Stiffness

Resilient materials can be flexed without breaking. Stiff materials cannot be easily bent (CES Edu, 2009).



4.30 Expression through Materials

The choice of material in each of these products expresses, in part, functionality and, in part, desired aesthetics: (a) PTFE, (b) acrylic, and (c) aluminum. (Bicycle image courtesy of MAS Design.)



properties are mapped in 4.28. There is a striking correlation between them: as a general rule materials that are difficult to scratch are also stiff.

Resilience and stiffness are a little more complicated. Resilience is the ability to absorb deflection without damage – a car tire is resilient; it can be driven over a curb and survive. Stiffness is resistance to deflection, measured – for a given shape – by the modulus of the material. These behaviors can also be expressed in terms of technical attributes. They are mapped in 4.29. Note that steel and other metals are stiff but not very resilient. Rubber and many polymers are resilient, but not at all stiff.

Conclusions

There is a school of design thinking that holds as a central tenet that materials must be used “honestly”. By this they mean that deception and disguise are unacceptable – each material must be used in ways that expose its strengths, its natural appearance, and its intrinsic qualities. The idea has its roots in the tradition of craftsmanship – the potters use of clays and glazes, the carpenters use of woods, the skills of silversmiths in crafting beautiful objects, each exploiting the unique qualities of the materials with which they work – an integrity to craft and material.

This is a view to be respected. But it is not the only one. Design integrity is a quality that consumers value, but they also value other qualities: humor, sympathy, surprise, provocation, even shock. You don't have to look far to find a product that has any one of these, and often it is achieved by using materials in ways that deceive or inspire. Polymers, as we have said, are frequently used in this way – their adaptability invites it. And, of course, it is partly a question of definition – if you say that a characterizing attribute of polymers is their ability to mimic other materials, then using them in this way is honest.

Honesty and authenticity are an important part of design, but so is invention and expression. There are moments in the design process when we need to use materials to create structure and surface that is simple and pure. But there are just as many moments when we need to use materials to create iconic behaviors and corporate logos. Both are a necessary part of good design, and it is these elements of materiality that make a product successful in the market and a classic in the eyes and minds of design history.

So we end this chapter with the question: to what extent can the attributes of materials – technical, aesthetic,

perceived – be used for expression? There are some obvious examples. Gold, silver, platinum, diamond and sapphire have associations of wealth, success, sophistication and lasting value; used in a product they give it the same associations. Carved or polished wood suggests craftsmanship; ceramics suggest elements of luxury or extreme performance requirements. Metals, generally, are recognizable as metals; a product made from them acquires the attributes of industry and strength as part of its personality almost immediately. But polymers can – at least in appearance – assume the character of almost any material; in particular, they can be made to look like metal, or like wood, or even like glass. Some example products are shown in 4.30: Gortex (or PTFE) in running shoes; acrylic in tail lights; nylon and aluminum in the folding bicycle. The beauty that designers need to find in plastics is the ability to do something with them that is impossible in any other way. And, as with all materials, we need to be careful and considerate about how they can and will be recycled. Design and expression are not intended to be frivolous, there is meaning in each step of the process, and we need to be thinking about ideas that are sustainable not just cool or new.

Further Reading

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Chapter 5

Manufacturing: Shaping, Joining, and Surfaces




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If you want to make something out of a material you need a process. Processes create shape, they allow parts to be joined, and they impart textures, finishes, or coatings that protect and decorate. Processes must be matched to materials – the processes that can shape or join polymers differ from those that can do the same to ceramics or glasses or metals, and even within this family, the process must be matched to the polymer type. Here we review the technical attributes of processes and explore the features they possess that contribute to the industrial design of a product.

The Engineering Dimension: Technical Attributes



Classifying processes is not as easy as materials. For materials, an unambiguous classification could be built on the scientific understanding of the bonding between atoms or molecules. But processes are devised by man, not dictated by nature – science does not help much here. The best approach is to classify according to the purposes for which the process will be used, though ambiguities are unavoidable. One adapted to their use in technical design is shown

in 5.1. At the highest level, processes are segregated into the three families suggested above, which we will abbreviate as *shaping*, *joining*, and *surface*. Each of these is developed in the way shown in 5.1, partly expanded to indicate classes and members.

For shaping, the first question is “how can I shape this material?” The classes of shaping are organized, as far as this is possible, by the families of materials to which they can be applied and the underlying similarities between the processes themselves. Each has many members (5.1, top row). Technical data for



5.1 A Classification of Processes

Based on groupings that are familiar to engineers. The final column shows a list of possible attributes for a specific process. Top, Classification of Shaping Processes; center, Classification of Joining Processes; bottom, Classification of Surface Processes.

each member define its attributes – the details of the shapes it can make and the restrictions it imposes on size, precision, and cost, as indicated in the last column of the figure.

The choice of process is determined by the materials to be shaped, the shape itself, and the economics of the process. When the material is a thermoplastic and the shape is complex, with doubly-curved surfaces, economics favor injection molding (5.2). Steel molds are very expensive, so for very small batch sizes (around 10) an epoxy mold is used; for 100, a metal-filled epoxy mold just survives; for 100,000, tool steel is necessary, and above that only molds of Stellite (an alloy based on cobalt, tungsten, and chromium) suffice.

Metals compete directly with polymers in filling these roles. Die-casting (5.3) of aluminum and magnesium alloys allows economic production of complex shapes with double curvature. Pressure die-casting is faster and so cheaper for larger batch sizes than gravity die-casting. As with injection molding, dies are expensive. Aluminum has a small

solubility for iron, limiting the die-life of steel molds to about 100,000 parts. Magnesium has no solubility for iron, giving an almost unlimited die-life.

High labor costs and low material costs have created a society that discards many products after a single, often trivial use. Such things must obviously be made by very low cost processes. Yogurt pots, butter containers, soft-drink bottles, and such are made by pressing or blow molding. The dies are cheap, the process is fast, and decorative labeling can often be molded in at the same time. Sheet pressing of metals, too, can be fast, cheap, and can be decorated in a continuous process (think of soda cans).

Joining processes are classified in a similar way (central tree of 5.1). The first distinction, giving the classes, is the way the joint is achieved – by adhesives, by welding, or by fasteners. Beyond the classes lie the members. The last column suggests the nature of the technical data that characterizes them.

The last tree (5.1, bottom row) shows a classification for surface processes. Almost all manufactured parts are given



5.2 Injection Molding and Die-Casting

Injection molded plastic (left) and die-cast metal (right).

1. Some texts give a broad survey of processes, others specialize in one of the classes of 5.1. [Lesko \(1999\)](#) and [Swift and Booker \(1998\)](#) give good introductions; but the bible is [Bralla \(1998\)](#), comprehensive, but not a book you'd read for pleasure. Of the more specialized texts, [Houldcroft \(1990\)](#) gives a good survey of welding processes; [Wise \(1999\)](#) gives more specialized information for the joining of polymers; and [Grainger and Blunt \(1998\)](#) detail processes for surface coatings for technical applications. We have been unable to find any text that deals with surface processes with predominantly aesthetic function – though the later part of this book goes some way to correcting that.

2. The ASM offers its 20 volume *Metals Handbook*, and the *Desk Editions* of both the *Metals Handbook* and the *Engineered Materials Handbook*, both on CD and the Internet, allowing rapid searching for text about all types of processes. The [Cambridge Materials Selector, CES 4 \(2002\)](#), contains datasheets for about 120 processes of all types, combining it with an advanced search engine.

3. An example can be found in [Poeton \(1999\)](#), “The Poeton Guide to Surface Engineering,” www.poeton.co.uk/pands/surface/.

a surface treatment of some sort. The reasons are diverse: to make the surface harder or more scratch resistant, to protect against corrosion or wear, or to enhance the visual and tactile qualities of the finished product. There are many different ways of doing each of these, shown in the second level of 5.1: chemical, mechanical, painting, printing, and so forth, each with many members. The final column again suggests the nature of technical data for a member.

Technical data for the members of 5.1 can be found in texts on processing,¹ in software,² and in suppliers' datasheets.³ Profiles for 65 of the most important of these are given in the second part of this book.

The Other Dimensions

Processes influence the ergonomics, aesthetics, and perception of products and of the materials of which they are made. Shaping gives form. The shapes of which a process is capable are clearly important here: extrusion, for instance,

allows only prismatic shapes, whereas die-casting of metals and injection molding of polymers allows shapes of great complexity. Joining – an essential step in the assembly of a product – can also create contrasts and other expressive features: some processes give near-invisible joints, others allow them to be prominent. Surface processes, particularly, influence aesthetics and perceptions through color, reflectivity, texture, and feel, and they are also important for ergonomic reasons, creating the visual and tactile communication with the user. We explore them by examining expression through processing.

Expression through Shaping

Creating form is one of the earliest forms of human expression: carved stone and molded pottery figures, beaten ornaments, and cast jewelry predate any documented ability to write or draw. The sculpture, pottery, and architecture of today are evolutionary descendants of these prehistorical antecedents and still use many of their processes: molding (initially with clay, now with polymers), carving (now a subset of machining), and lost wax (now investment) casting. Shaping, here, is a channel for self expression.

[Figure 5.3](#) shows one way in which form and materials have been used to create different aesthetics and perceptions. The lamp uses ABS and acrylic formed by thermal forming and injection molding; in both its folded and its unfolded state it is perceived as humorous, friendly, appealingly dotty yet completely functional. The

5.3 Expression through Shaping

The bird lamp expresses its humor through shape.





tape dispenser expresses a sense of humor and surprise in both its biomorphic form and bizarre color.

Expression through Joining

Joining reaches an art form in book binding, in the dovetailing of woods, and in the decorative seaming of garments. In product design, too, joints can be used as a mode of expression (5.4). The fuel cap of the Audi TT machined from stainless steel and attached by eight Allen screws, is an expression of precision technology that implies the same about the rest of the car. The prominent welds on the frame of a mountain bike express the robustness of the design. Deliberately highlighted joints are used as decorative motifs, often to emphasize the function of the product. Co-molding of two contrasting polymers to form the toothbrush both decorates and highlights the different functions of the two (one structural, the other to give grip).

Expression through Surfaces

One could describe the paintings and prints of the world's great museums as surface treatment elevated to the status of high art. Both techniques have been adapted to the more lowly task of product design. These, and a range of others,

some very ingenious, allow expression in a number of ways.

The late 20th and early 21st centuries are addicted to flawless perfection.⁴ Makers of earth-moving equipment have long known that – if their products are to sell – they must deliver them with the same high finish that is required for a passenger car. And this, despite the fact that the first thing a purchaser does is to lower the equipment into a hole half full of mud to start digging. It is because the perfection of the finish expresses the perfection of the equipment as a whole; a poor finish implies, however mistakenly, poor quality throughout.

So surface processes can serve to attract, as with the digger. It can suggest, sometimes with the aim of deceiving; metalized plastic is an example. It can surprise, adding novelty – a jug kettle with a thermo-chromic surface coating that changes color as the water heats up. It can entertain: holographic surface films can suggest something lurking inside the article to which it is applied. It can add function: non-slip coatings add an ergonomic function, and technologies for printing electronic circuitry onto products give them sensing and information-processing functions.

5.4 Expression through Joining

The contrasting co-molded handle of the toothbrush emphasizes its structural and ergonomic functions.

4. Perfection and Imperfection. Surface perfection is violated by the slightest defect – it has no hope of aging gracefully. Better, to make visual imperfection a part of the personality of the product – something that gives it individuality. It is this, in part, that makes natural materials – wood, leather, and stone – attractive.

5.5 Expression through Surfaces

Sunglasses coated with metallic blue create a unique surface detail.



Designers often create expressive elements through surface treatment. Screen printing is used to distinguish surfboards, board style, and personal style. Bead blasting of a glass surface gives a frosty sense of elegance. The metal oxide coated sunglasses express high-tech fashion through brilliant, reflected color (5.5).

Expression through Manufacturing

There are travel trailers (RVs or caravans) and there is Airstream (5.6). Most travel trailers are built like sheds. Airstreams are built like aircraft. It is not just the

choice of material – they are, of course, made of aluminum and have been for over 70 years – it is not just the material but also the manufacturing methods that creates the style. The body is a monocoque shell joined not by welding (as in auto construction) but with deliberately visible rivets. The finish exposes the bare metal surface (paint is the norm for automobiles) emphasizing the aircraft antecedents. Here is a product that derives its quality (reflected in its price) from its use of materials and from the choice of forming, joining, and finishing processes used to make it.

5.6 Expression through Manufacturing

Manufacturing details and quality can communicate a lot about a company and its products (Image courtesy of Airstream Inc. Jackson Center, OH).



Conclusions

The aesthetics of a product are created by the materials of which it is made and the processes used to shape, join, and finish them. Ideas are expressed and perceptions and associations created by the ways in which these are used. The technical requirements of the product impose certain constraints on shape, but within these there is still room for expressing quality, or humor,

or delicacy, or sophistication. Joining, too, can be used to suggest craftsmanship, or robustness, or to differentiate parts of the product that have different purposes. Above all, surface treatments modify color and reflectivity, texture and feel, and can add pattern, symbol, or text to instruct, amuse, or deceive.

The latter part of this book contains profiles for some 65 processes, chosen because of their importance in product design, that bring out these features.

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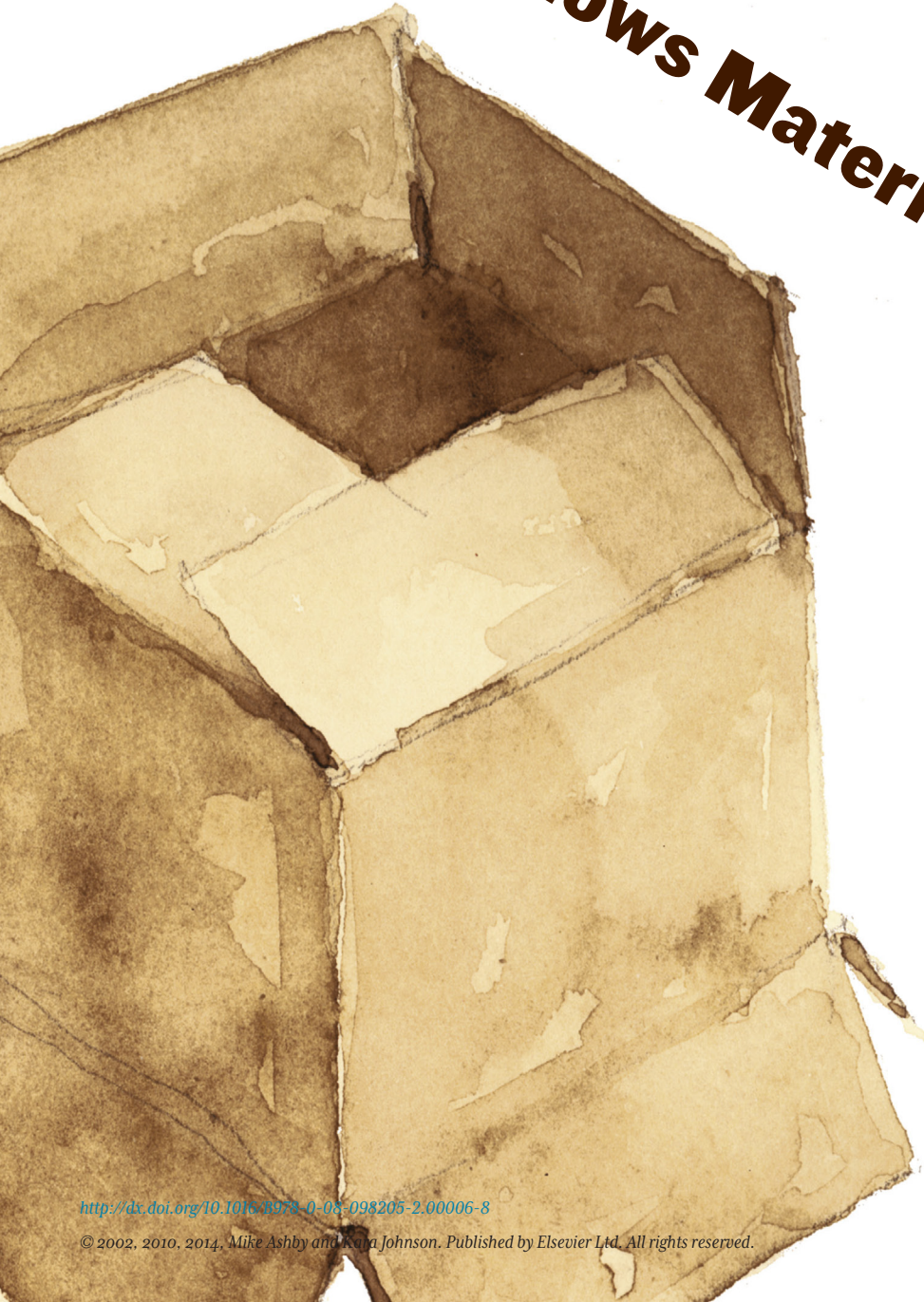
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Chapter 6

Form Follows Material



Materials exert a profound influence on the form of products. Nowhere is this more visible than in architecture. The Parthanon, the Eiffel Tower, the Golden Gate Bridge, all great symbols of their age, are unique expressions of what is possible with a particular material. An Eiffel Tower made from stone is as inconceivable as a Parthanon made from wrought iron or a Golden Gate Bridge made of reinforced concrete. The material has constrained each design, but within these constraints the designer has created a form that subsequent generations see as structural art.

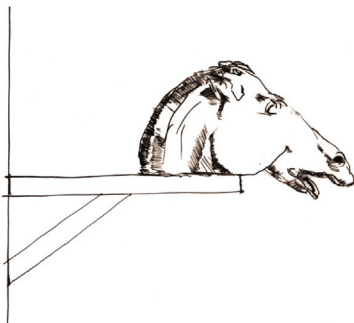
Materials and Architecture

The most direct links between material and form arise through the forces that materials can carry (6.1). To bring out the point, look at the images of 6.2, each pair illustrating the forms that are made possible – even forced onto the design – by the nature of the material of the primary structures. Stone and cemented brick

(6.2a and b) are strong in compression, weak in bending and tension, requiring designs that transmit loads by compression: closely spaced columns (a) or compressive arches (b). Wood is strong in tension, compression, and bending, allowing triangulated space frames or trusses (c) and cantilevered structures (d). Early cast iron (e and f), like stone, is brittle in tension or bending, forcing

6.1 Bending, Tension, and Compression

Three ways of supporting a heavy object. Its mass exerts a load on the support. If a material that can support only compression, such as stone, is to be used, the form must resemble that in the center. If a material is strong in tension but cannot support compression or bending, as is the case with strong wires or fibers, then a suspended form like that on the right is required. If a material that can support bending, like wood or structural steel, is to be used, the form on the left becomes possible.



6.2 Bridges of England

(a, b) The forms of these structures are dictated by the brittleness of the stone, making it strong in compression but weaker, by a factor of about 20, in tension and bending. Brick, like stone, is strong only in compression.

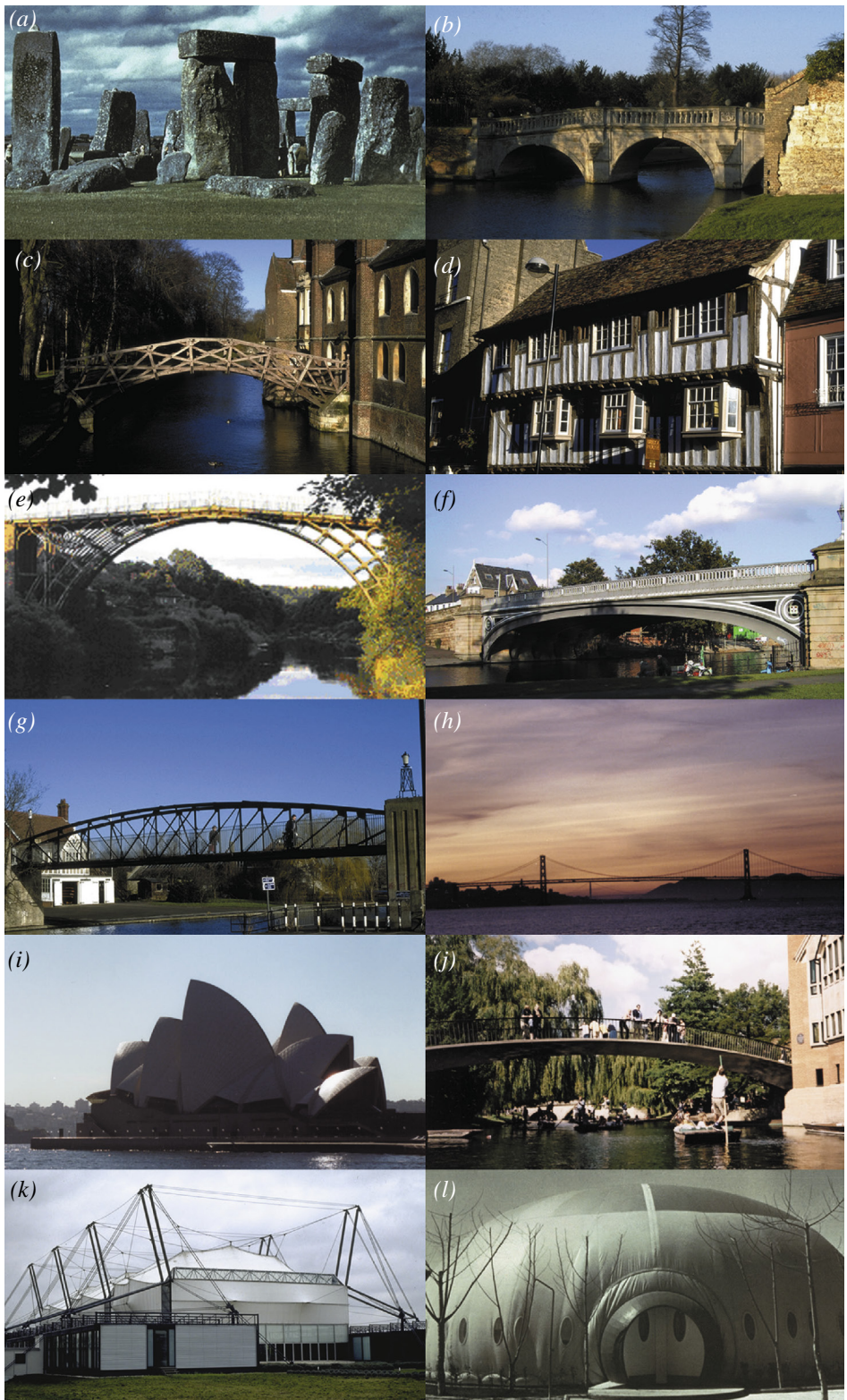
(c, d) Here the forms reflect the high strength-to-weight ratio of wood, and its ability to carry both tensile and compressive loads almost equally well.

(e, f) Here the forms reflect iron which can be cast to intricate shapes, but also its relative weakness in tension and bending.

(g, h) Steel in the form of I-sections carries compression and bending efficiently; drawn to high tensile cable, it is very efficient in tension. In the explicit design of these structures the orientation of the struts reveals the directions in which the forces act.

(i, j) Reinforced, and pre-stressed, concrete allows great freedom of shape and delicacy of form. The materials, a composite of steel and concrete, carry tensile, bending, and compressive forces equally well.

(k, l) Left: high tensile steel cables with truss-like compression members supporting a glass-reinforced PTFE room membrane; Right: a rubberized nylon membrane supported by internal pressure. The forms are a direct consequence of the choice of material.



designs that follow the column/arch principle to transmit loads by compression, but – because of the ease with which it can cast to delicate shapes, it allows a new lightness to appear in the structure. Wrought iron (g) and steel (h) overcome the brittleness problem of stone and cast iron, allowing slender members that can carry tension or bending, stimulating further development of the space-frame concept. Reinforced concrete, too, has tensile as well as compressive strength, and the ease with which the reinforcement can be shaped allows fluid, shell like structures (i,j). Fabrics and high tensile steel cables carry tensile loads well but cannot carry bending or compression (they buckle) leading to another set of forms (k,l).

In all these examples, materials have been formed into elements capable of carrying certain forces; the elements are integrated into forms designed to convert the loads on the structure into forces that are compatible with the material of which it is made. Most of the buildings in 6.2 were devised before the science of stress analysis had developed, but even without it, the designer was capable of visualizing the forces and the relationship between force, material, and form. In every case, the form of the building has been powerfully influenced by the nature of the material of which its structure is made. Form, you might say, follows material.

Materials and Products

Many designers – like the Bouroullec brothers – manipulate material and geometry to take us on a journey that is about more than an exploration of form. They create improbable and beautiful expressions of materiality with deep meaning and powerful aesthetics. These expressions are not always applicable in the factory but their exploration of materials inspires product designers and industry in general to push the boundaries in mass production.

As an example, chairs must meet certain obvious mechanical constraints, but they are not severe, leaving room for diversity both in choice of material and in form. The form is not particularly limited by the function – if it were, all chairs would look the same, and a glance at 6.3 shows that this is clearly not the case. But once the material is chosen the form is constrained.

A chair, you might think, has two basic components: a frame to carry the mechanical loads, and a seat to adapt the frame to the shape of the person who will sit in it. The chair of 6.3a has these features: the frame is tubular steel and the seat is molded, corrugated polypropylene. In 6.3b, the use of a steel wire mesh, that is formed, soldered, nickel-plated, and coated with epoxy combines the frame and the seat in 'one. In 6.3c, Philippe Starck has manipulated polypropylene to create a molded seat that



(a)



(b)

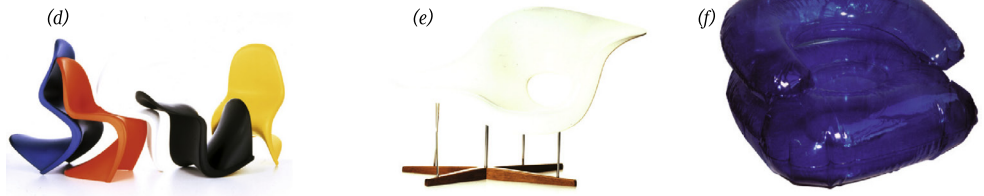


(c)

6.3 Chairs

The chair is one of the most common forms manipulated by industrial designers or engineers; some unusual forms and materials are shown here. (Images courtesy of Vitra Museum and Hans Hansen)

6.3 Chairs, continued



1. *Functionality is a measure of how well a product meets its technical expectations. Personality measures the degree to which it provides emotional delight and satisfaction in ownership. Thus a desk lamp could – by providing light of the right intensity at the right place – have high functionality, yet – by having a form, color, and feel that clashed with the rest of the décor – have low personality.*

6.4 Identification, Visualization, and Materialization

The steps in developing product form. The list implies a sequential process, but it is far from that.



is soft and playful. In 6.3d, the use of glass fiber-reinforced polypropylene allows the combination of the frame and seat in one. Charles and Ray Eames use fiberglass to create two shells, joined and bonded to a chrome-plated tubular steel base (6.3e). The last, 6.3f, is made of inflated pvc and has something of the bulbously pneumatic look of the inflated building of 6.2l. Here the frame has disappeared; the seat is also the support. As with buildings, the materials of the chair have profoundly influenced its form.

Thus there is more than one way to approach the selection of materials. One is through technical function. The other is through form and features, seeking materials capable of providing them. Here we explore the idea of form and features.

Identifying a Feature List

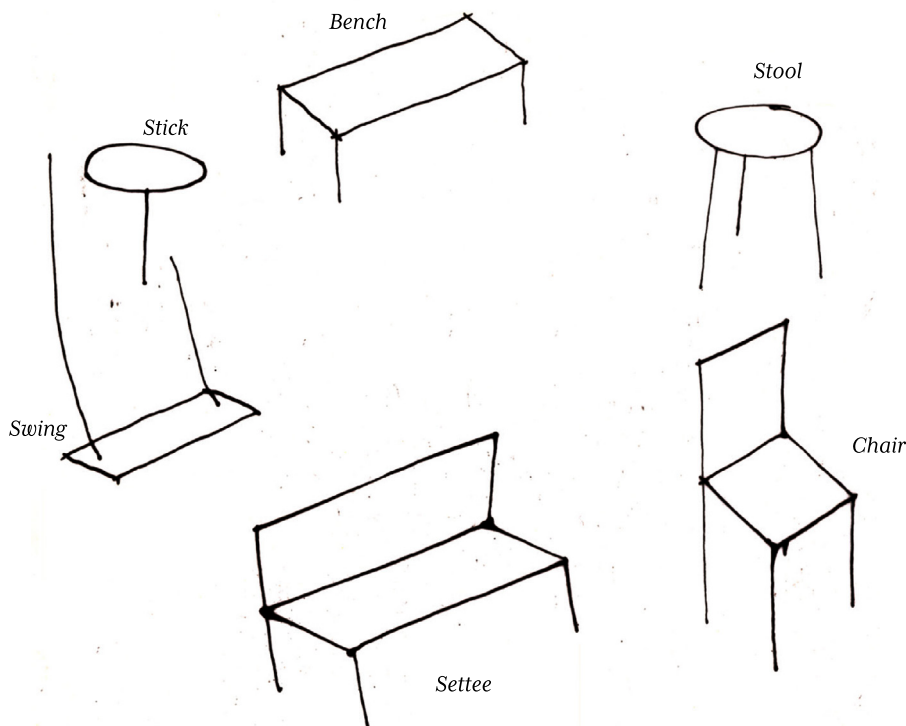
The act of design transforms a *need* into a *product*; it starts with a featureless abstraction and ends with a concrete reality. First some definitions. A *need* is an abstract idea. The need for “illumination” carries the idea of light, but says nothing whatever about its form, its feel, how it will be achieved, or how it will be perceived. A *concept* is one way in which the need might be met – a candle, an incandescent lamp, a fluorescent tube, a laser – and for each of these there is a set of possible subconcepts. A *product* is a realization of one of these; it is a concrete object, with forms and features that can be seen and touched. It is made by processes, using materials that themselves have visual and tactile behaviors. A *feature* is an aspect of the design that contributes to its functionality, usability, or personality.¹ Features are of many types. There are topological features, defining the configuration of the product. There are

geometric and dimensional features, some determined by technical requirements (strength, stability, efficiency, etc.), others by the needs of the user (ergonomic features), still others to give the product certain visual and tactile qualities. Beyond these, there are perceived features – those that create the associations of the product and the meaning it conveys. *Solutions* are combinations of features that embody the concept, making it real, and which do so in ways that, to some degree, meet the intentions of the designer. The solution that is chosen for manufacture becomes the product.

The starting point for developing form is the formulation of the desired features of a product. The features define the constraints to which the form and materials must comply. Formulating and applying constraints is central to any act of selection. Solutions that do not meet the constraints, applied successively, are rejected, until a manageably small subset remains. But while design-

ing includes the act of reducing the set of possible solutions, it importantly also contains also the act of expanding them. The designer, experimenting with ways in which the features are used, evolved and combined, visualizes new solutions. Thus moving from concept to product involves both narrowing the number of solutions by screening out those that fail to meet the constraints and expanding it by creating new solutions that are in turn screened. The feature list exerts the constraints and at the same time provides the ingredients of inspiration.

Features are identified, and solutions synthesized and screened in ways that we shall group under the headings Identification, Visualization, and Materialization (6.4). The sequential nature of a book – read in the order in which it is written – suggests that this is a linear progression, but that is not intended here. Using a text-based analogy: design, and particularly the creation of form, is not a linear procedure like



6.5 Concepts for Seating

The idea of "seating" can involve many concepts: some with four legs, some with none; some for one person, some for many.

6.6 Features of a Concept
“Chair”

A chair has certain generic features that constrain the form.

Configuration
Support one person
Horizontal seat
Back support
Scale
0.3 < Width < 0.4 m
0.7 < Height < 0.9 m
0.3 < Depth < 0.4 m

6.7 Intentions in Design

Intentions describe the broad visions that guide the design. A single product may have more than one dominant intention.

Market
Design for public use
Design for women
Design for the elderly...
Economics
Design for minimum cost
Design for assembly
Design for mass production...
Sustainable
Design for the environment
Design for recycling
Design for biodegradability...
Performance
Design for maximum insulation
Design for minimum mass
Design for minimum volume...

filling out a tax form (“if this, then that...”), it is more like a multidimensional crossword puzzle (“does this fit with these... or perhaps these are not yet quite right... what if we tried this instead...”).

Identification

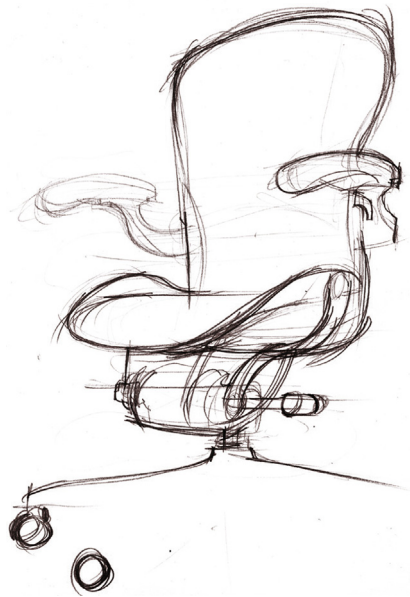
Identification of concept is the first step in developing a feature list for an initially abstract idea. We use the need for “seating” as an example. The idea is initially abstract: it has as yet no form. There are many possible concepts for seating – basic ways of providing support: the bench, the stool, the chair, the settee, the swing, the shooting stick, and many more, as suggested by 6.5.

We choose the concept “chair.” This is a concept that has been used before; and although we wish to have the maximum freedom in its design, the choice of chair implies that it will have certain generic features – features that are accepted characteristics of a chair. The chair stick-diagram of 6.5 illustrates these. They are of two types. The first has to do with configuration: a chair, normally, is designed to support one person; it has a horizontal seat, supported above the floor by legs or some equivalent structure, and it provides support for the back. This combination of generic features already differentiates it from all the other concepts of 6.5. The second type of feature has to do with scale. The chair is to support an adult; if it is to do this, the depth and width of the seat, and its height above the floor are constrained to lie within certain broad ranges. Thus the choice of concept has identified a set of

features, some constraining configuration, the others constraining scale (6.6). The creativity lies in choosing features and combining them into solutions that meet these constraints and, at the same time, optimally achieve the designer's *intentions*. That is a word that needs explanation. It comes next.

The features that characterize a chair for an airport differ for those of a chair for a nursery; each is designed for its intended use. The phrase “Design for x” nicely captures the way in which the features of the chair are selected with one or more broad underlying intentions in mind – here, design for public use, or design for children. This use of *intentions* to guide choice of features goes further than simple market objectives: design can be adapted to meet economic objectives, environmental objectives, and, of course, performance objectives. Figure 6.7 suggests the categories.

Consider, as an example, the design of an office chair (6.8), defining an intention – “design for the office,” some



6.8 Visualizing an Office

Chair

An office chair has certain required features: by legislation, in Europe, it must have five – not four – points where it touches the floor.

features of office chairs are required by legislation: an office chair, in parts of Europe, must have five, not four, points where it touches the floor. Others are identified by examining existing solutions to concepts for office furniture,



6.9 Visualizing an Office Environment

The environment in which the chair will be used suggests visual features that relate it to its surroundings and purpose, and to the aspirations of the user.

6.10 Feature List for Functionality

Technical and ergonomic features are required for products to function properly.

Functionality
Comfort
Range of motion
Adjustable
Strong
Stable
Easy to clean
Abrasion resistant

6.11 Feature List for Personality

Aesthetic and perceived features are required for each product's personality.

Aesthetics
Black
Metallic
Soft
Organic
Perceptions
High tech
Masculine
Expensive

seeking those that appear well adapted to other intentions of the design. Thus the prioritization of features in “design for light weight office equipment” is different from that in “design for recyclable office equipment.” The intentions provide filters through which features are screened. Indexing by intention allows the exploration of features of other products designed with the same intentions in mind (6.9).

A successful product is well adapted for the circumstances under which it will be used. The office chair will be used for many hours a day, and not always by the same person. It must offer comfort and be adjustable in height and in the angle of the seat and back. For freedom of movement it must rotate. It must be strong and stable – industrial injuries lead to damaging compensation. It must be durable, immune to coffee stains, and scuffing (6.10).

And finally there is its personality. Personality describes the associations and meaning that a product has for those who own or use it. Personality relies most heavily on the visual and tactile: a sense of order, proportion and internal coherency, and on shape, color, and texture. And it includes the sense of compatibility with the lifestyle and aspirations of the consumer. Features that create and transmit these visual messages become another part of the feature list from which the final solution ultimately emerges.

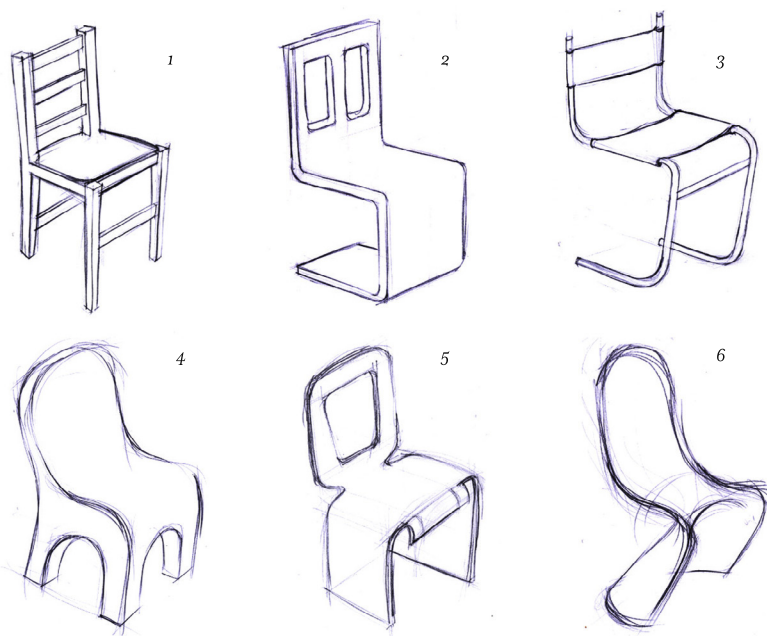
The easiest of these to describe in words are those of color, texture, feel, and form (see Figure 4.21 in Chapter 4). Perceptions are harder to express

precisely, and are usually described by loosely defined words or metaphors like “rugged,” “feminine,” or “classic” that suggest rather than define the perception, but still convey a certain set of features created by the choice of form and material. Figure 4.26 listed such words, drawn from reviews in design magazines and exhibition catalogs. Some that might apply to office chairs are listed in 6.11.

Visualization

Strategies for creating personality are found by examining the environment in which the product will be used and the ways in which other products in this environment succeed in creating a similar personality. A common technique is to assemble images of products or environments, color, and texture samples, and samples of materials themselves that exhibit some aspect of the personality that is sought. These are assembled into a collage or mood board allowing them to be moved, rearranged, and overlapped to suggest alternative combinations, as described in Chapter 3.

Building the feature list, as we have said, has the effect of narrowing and focusing the constraints on product form. But at the same time the list provides a tool for inspiration. The freedom to rearrange features can suggest new solutions, some of which may come closer to achieving the desired personality than any existing solution. It is a kind of visual “reasoning,” often supported by hand sketching, which, in this context, can be thought of as “data processing”; the “data” are the individual visual features.



6.12 A Material/Process Matrix for Chairs

Form is partly determined by the choice of material and process.

	Machining	Sheet Forming	Drawing	Rotation Molding	Lay-up Methods	Thermofforming
Solid wood	1					
Plywood					5	
ABS				4		6
Stainless steel	2	2	3			

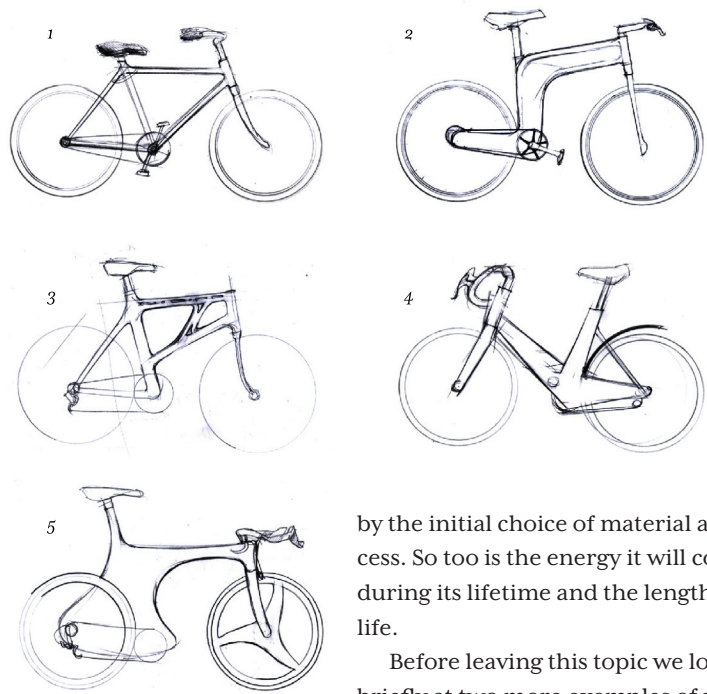
The feature list thus far defines both a set of constraints and a set of inputs to the creative synthesis of new solutions. But what can really be made? Actuality is limited by materials and by the processes used to shape, join, and surface them. They are, so to speak, the free variables of the design; their choice makes possible a range of solutions.

Materialization

Figure 6.12 illustrates the way in which the choice of material and process can allow different groups of features. The matrix lists four materials and six processes.² The numbered boxes mark combinations that are explored in the sketches. Each combination leads to forms that have characteristic features: lamination of wood (chair 5) is well adapted to structures with flat planes or

single curvatures; rotational molding (chair 4) gives closed hollow structures with doubly-curved surfaces. The choice also influences the aesthetics of the product – color, texture, and feel. Wood (chairs 1 and 5) is naturally textured, it is light in weight, and it feels warm. Stainless steel (chair 2) is metallic and reflective, heavy, and cold. The degree to which these combinations match the desired feature list is the metric of success. It is here that technical and industrial design reasonings merge. Materialization – creating an object that can be seen and touched – is partly conditioned by choice of material and process, partly by the necessity that the product carries design loads safely, and this is established by standard methods of technical design. The environmental impact of the product, too, is influenced

2. Profiles for most of these appear at the end of this book.



6.13 A Material/Process Matrix for Bicycles

The matrix suggests possible combinations of material and process; the empty spaces represent opportunities or limitations.

by the initial choice of material and process. So too is the energy it will consume during its lifetime and the length of this life.

Before leaving this topic we look briefly at two more examples of material and form: the bicycle, and the bottle opener.

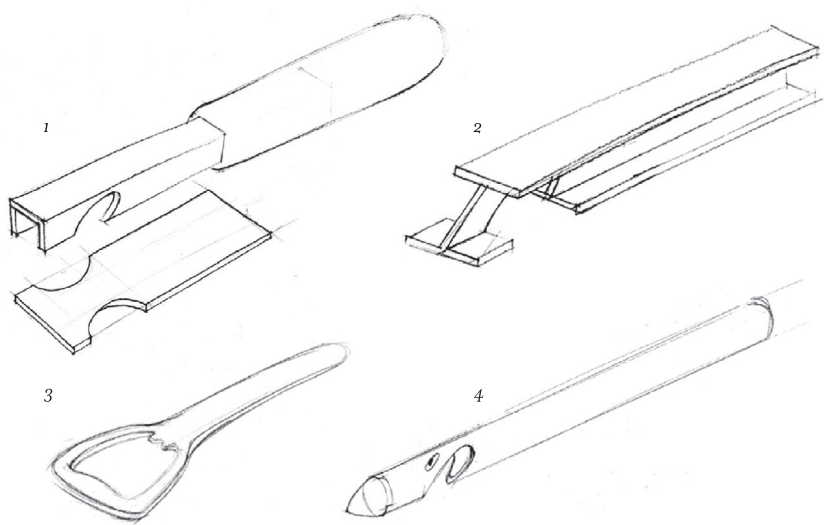
The Bicycle: Materials and Form

Bicycles are made in a great diversity of materials and forms (6.13). The requirements here are primarily mechanical – strength and stiffness – to be achieved at low weight and acceptable cost. The triangulated space frames convert the forces generated by the rider into tensile, compressive, and torsional loads in its members, like the architectural space frames of 6.2c and g; the materials are chosen and shaped to carry these loads. Early bicycles had a solid hickory frame joined by adhesives – they were light but not very durable. Solid steel is 10 times denser than wood, but shaped into a hollow tube and joined by

brazing it is as light as wood for the same stiffness and strength (form 1 of 6.13). Most metals can be drawn to tube, so that metal bicycles frequently have this form.

But joining, for some materials, is difficult, slow, and expensive. Might it not be possible to make a frame with fewer parts, or even as a single integral unit? Form 2 shows a frame made by pressing and adhesively bonding two aluminum sheets to give a light, hollow shell. Form 3 uses injection molding to integrate parts into a single unit; here both the frame and wheels are single nylon moldings. Made in large numbers, moldings can be cheap, and nylon, unlike steel, does not rust. There is, however, a problem: nylon, even when filled, is more than 50 times less stiff and 10 times less strong than high strength steel, requiring that the cross-sections have to be larger. The chunky, heavy appearance of a polymer bicycle is the result; it looks clumsy – an unfortunate personality for a bicycle. If not injection molding, why not die-casting? Magnesium is light and easy

	Extrusion, Drawing	Sheet Forming	Die-Casting	Injection Molding	Lay-up Methods
Steel	1				
Aluminum		2	4		
Magnesium			4		
Nylon				3	
CFRP					5



	Stamping, Press Forming	Injection Molding	Extrusion	Stamping
Steel	1		4	3
Thermoplastic		1		
Aluminum			2	

6.14 A Material/Process Matrix for Bottle Openers

Again, the matrix can also suggest possible combinations.

to die-cast. But tubes can't be die-cast; an I-section of equivalent stiffness can. Form 4 is the result – a form dictated by the choice of process and material. The lightest, stiffest material choice for a bicycle is CFRP (an epoxy resin reinforced with carbon fibers). Early CFRP bicycles used tubes, emulating the steel bike, but joining them was difficult, and the joints added weight; the form did not make good use of the material. The properties of CFRP are better utilized in a mono-coque construction (a shell-like skin), as in form 5.

In each of these examples the form reflects the properties of the material and the ways in which it can be processed.

Bottle Openers: Materials and Form

A bottle opener performs a simple mechanical function: it captures the rim of the cap with a tooth and – when

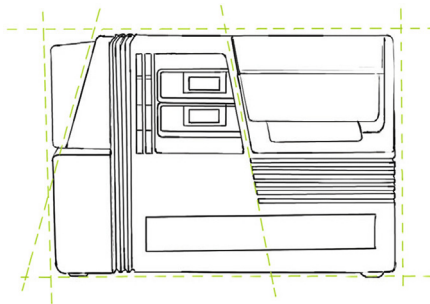
leverage is applied to the handle – lifts it off. That's one concept (there are others) and it implies certain constraints on configuration and scale. It can be embodied in many ways, a few of which are sketched in 6.14. That at (3) is stamped from flat sheet steel. Those at (2) and (4) start with an extruded section, requiring materials that are easy to extrude. That at (1) is made by stamping and folding of steel sheet, with a polymer handle molded on.

Matrices³ like those of 6.12–6.14 are a useful way to explore materialization, and have the ability to suggest ways in which material-process combinations might lead to new solutions.

Before concluding this chapter it is interesting to switch perspective briefly – to think not of the designer designing, but of the observer analyzing the origins of a design. What can be inferred about a product from its

3. The suggestion originates with Haudrum (1994).

6.15 A Small Compressor



features? Let us consider the connection between material and form in other fields of research.

The Compressor: Design Language

The photo shows a small, very cheap, 12 Volt compressor designed as an

emergency tool for motorists (6.15). What associations and perceptions are the designer trying to create? What, in a word, is he trying to say? The next two frames analyze the sources.

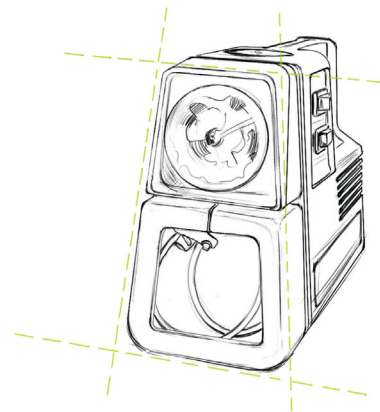
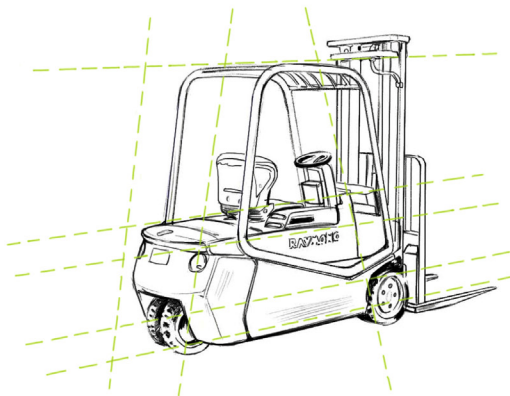
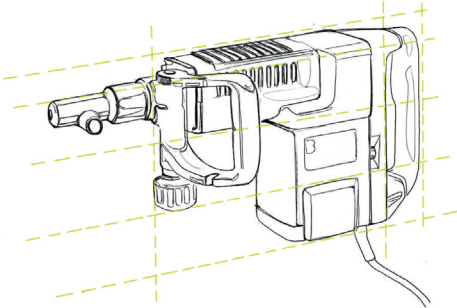
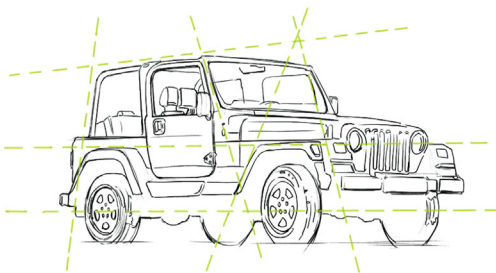
The other products shown as 6.16 give visual clues. All three epitomize “industrial strength” design expressed through form, color, texture, and graphics. They have certain features in common:

- Angular, straight-edged forms.
- Repeated horizontal.
- Upward-converging diagonals.
- Subdued color.
- Use of texture to create contrasts.
- Minimal decoration

These are exactly the design features the designer has adopted for the compressor.

6.16 Elements of Strength

A professional hammer drill, a fork-lift truck, an off-road vehicle and a small battery driven air pump.



The associations are those of power tools and commercial or military vehicles, the perceptions are those of robustness and fitness for purpose. The message is: this is not a toy, it is a serious bit of kit.

Household Appliances: Design Language

We conclude this section with an example of visual re-design, the creation of students at the Department of Industrial Design at the Helsinki [University of Art and Design \(Uiah\)](#) in 1995. The task was to re-design a set of five small household appliances – a hair dryer, an iron, a shaver, a toaster, and a mixer – in 12 different stylistic “codes.” A code is a style-language that evokes certain associations and emotions through the use of form, color, and texture. The results, published in an exhibition and as a book, are amusing and provocative.

Three are reproduced here. For the first (6.17) the code is conservative, discrete luxury, captured by the use of dark colors and wood-like textures contrasting with matte and gloss-finished metallic surfaces. The second (6.18) adopts a toy-like code eliciting simplicity, friendliness, and humor achieved through clear rounded forms and primary colors that distinguish functional parts. For the third (6.19) the code is rugged and uncompromisingly functionality, achieved through hard angular shapes with non-reflective blacked metal finish.

These are examples of style for style's sake, and as such might be seen as shallow and frivolous. But viewed in the context of design exercises they become



6.17 Elements of Style
A familiar product (an iron) characterized by understated modernist form, subdued color, and subtle texture. (Source: *The KOODI CODE*, U. of Arts and Design, Helsinki, Finland).



6.18 “Cute and friendly.”
The Mixit mixer. (Source: *The KOODI CODE*, U. of Arts and Design, Helsinki, Finland).



6.19 “Robust, military-strength, no-nonsense functionality.”
The Kalashnikov mixer. (Source: *The KOODI CODE*, U. of Arts and Design, Helsinki, Finland).

4. [Fagan \(1999\)](#) gives a readable account of archeological methods.



6.20 Sumarian Plates

A Sumarian silver dish with beaten and incised pattern and decoration.



6.21 Art Deco (Clarice Cliff) Plates

The material and form, and the color and geometry of the decoration, typify the Art Deco movement.

satirical caricatures, wittily exposing how association and perception can be manipulated by design.

Before concluding this chapter it is interesting to switch perspective briefly – to think not of the designer designing, but of the observer analyzing the origins of a design. What can be inferred about a product from its form and other related details? Let us consider the connection between material and form in other fields of research.

The Inverse Process: Product Archeology

An archeologist, unearthing an incised and patterned object like that of 6.20, seeks to infer from its features the needs and desires that inspired its making. Its diameter and slightly concave shape imply the concept: a plate or dish. Its shallowness and absence of rim are features suggesting its functionality: used to hold solids, not liquids. The geometry of the design associates it with other, previously discovered, artifacts with different forms and imagery but with the same style: the proportions, the geometry of the patterning, the material, and the way it was worked. This in turn associates the plate with a period, a society, and a culture – that of the Sumerian civilization – about which much is already known. The material and the process – silver, beaten and incised – and the quality of the workmanship begin to give meaning to the dish: silver and the skills to work it have never been resources to which the average man could aspire. The

perception of the plate, then as now, was of a rare and precious object, the possession of an individual or organization of wealth, importance, and power – the last reinforced by the image of the lion.

This kind of archeological method is known as “Typology.” Its basis is that of clustering objects into groups (“types”) that share the same attributes of material, form, and surface decoration. Behind it lies the premise that objects from a given time and place share a recognizable style – what today would be called a “brand identity” – and that changes in style are gradual. Three broad groups of attributes are used in Typological Archeology, and they are revealing. This is the way one well-known text⁴ describes them:

- *Formal attributes* are features such as shape, measurable dimensions, and components.
- *Stylistic attributes* include decorations, pattern, color, and surface finish.
- *Technological attributes* are those describing the material and process used to make the object.

The parallel with the feature lists developed in this chapter, based on current design thinking, is striking.

Let us try it on a 20th century design. The object shown in 6.21 is the work of a design house – Clarice Cliff – and epitomizes a style – Art Deco – that gripped both Europe and the US in the 1920s. Art-Deco styling invokes semi abstract geometry involving horizontals, zigzag lines,

and dynamic streamlining. Geometric ornamentation is based on hexagons, octagons, ovals, circles, and triangles. Decoration is borrowed from classicism; pre-Colombian, Egyptian, and African art using motifs such as the fan, the lotus-blossom, the rising sun, and the lightning strike. Art Deco was the first style movement to make expressive use of polymers. Bakelite (a phenolic resin), the first commercial plastic that could accept a wide range of colors and textures, lent itself to the adventurous curved and terraced shapes of the Art Deco movement – shapes that would be hard to make from wood. At one extreme, that of the portable radio, the use of plastic, chrome, steel, and aluminum allowed a range of cheap mass-produced products. At the other, that of state rooms of great ocean liners and grand hotels, the use of exotic hardwoods, leather, ivory, glass, and bronze created a décor for the very rich. The associations of Art Deco are those of cosmopolitan luxury, industrial progress and power, faith in technology, and futurism.

Some design styles, such as those listed earlier (4.27), have such significance that they have been studied in depth; the cluster of attributes – form, pattern, decoration, material, and process – that characterizes each is well documented. But many other “styles” exist that have arisen naturally in attempting to meet a need. Thus there is a style associated with military vehicles that has its origins in purely practical needs, with the obvious associations of rugged durability, toughness, and aggression. Car designers, particularly

designers of off-road vehicles, draw on the form, color, and material of military vehicles to create, in their products, the same personality. There is a style associated with electronic equipment in aircraft and ships, again purely utilitarian in origin, which carries associations of cutting-edge technical performance, precision, and reliability. Designers of high fidelity equipment for the connoisseur use the visual prompts of this style – understated rectangular form, matte-black finish, switches, and controls that mimic those of the professional equipment – to suggest unpromising technical leadership. There is a style that characterizes aerospace that goes beyond simple streamlining, extending to color and material (polished or matte aluminum), shapes of windows and doors (rounded), and method of joining (riveting). Designers of household appliances use these and other characterizing attributes of aerospace to suggest associations with the advanced nature of that industry.

This digression into archeology has a point. It is that the methods of typology allow products to be indexed in a number of ways: by configuration, by scale, by intention, by functionality, by personality, and by the materials and processes used to make them. A catalog, of products indexed in this way (or a software-based equivalent), becomes a tool for industrial design, a kind of computerized collage or mood board, and yet another way of suggesting materials and processes. This idea is developed further in Chapter 7.

5. Sullivan was an architect, a designer of skyscrapers. His phrase laid down a basic principle of modernism, and with it a misunderstanding that has proved as hard-wearing as concrete. It has become an alibi for products with brutish lack of imagination. Sullivan himself explained what he really meant, namely that building banks that look like Greek temples is ridiculous – after all, the clerks behind the counter do not wear togas. A bank that serves its purpose should look like a bank; a museum like a museum; a residential building; like a residential building.

Conclusions

One of the most quoted and influential phrases of design history is “form follows function.” Its originator, Louis Sullivan, had a simple point he wished to make,⁵ but its brevity, its alliteration, its practicality – its *neatness* – gives it a compelling quality, seeming to say that the best form for a product is that which best fulfills its function. This reasoning has an obvious appeal to engineers, whose job it is to make things function, and there are many instances in which the pursuit of function has created a thing of beauty: the Golden Gate bridge in San Francisco, the original Volkswagen Beetle, the Concorde aircraft (though the Boeing 747, it could be argued, is nearer to the “form follows function” principle) – all these were designed with technical rather than aesthetic challenges in mind. Perceptions like these have given the phrase the status of a religious dogma.

But can it really be true? Is the best design – the only design – that which best fulfills its function? Form, as just shown, is also influenced by materials; in the case of architecture, the influence is strong; in product design, though sometimes less obvious, it is certainly present. A case could be made for the dictum “form follows material” – it doesn’t sound

as good but it may be closer to reality. It seems to be a general rule that good design uses materials in ways that make the most efficient, and often visible, use of their properties and the way they can be shaped. Rules, of course, have their exceptions: incongruous use of materials can convey the surreal (a furry watch) or the ridiculous (a knife blade made of rubber) or transfer an association from one object to another (chocolate Eiffel Towers). All have their small place. But at the center of the stage are forms that use materials elegantly, efficiently, and economically.

And function and material are not the only directors of form. Consumers buy things they like; and with many alternatives of nearly equal technical merit, the consumer is influenced by trends in taste, by advertising, and by the things that other people buy. Form, inevitably, follows fashion. There are still other drivers of form. Form follows delight. The near-satiated society of 2000+ is attracted by humor (the Snoopy hair dryer, the banana telephone), by perfection (the immaculate body paint of a new car), by luxury (deep, soft leather-upholstered furniture), and by whimsical novelty (any Philippe Starck design). Product form is influenced by many things, but material and process are among the strongest.

Further Reading

Bahn, P. (1996) "Archaeology – A Very Short History," Oxford University Press, Oxford, UK. ISBN 0-19-285379-1. (A lively, critical and entertaining survey of archeological methods and schools of thought.)

Billington, D.P. (1985) "The Tower and the Bridge, New Art of Structural Engineering," Princeton University Press, Princeton, NJ, USA. ISBN 0-69102393-x. (Professor Billington, a civil engineer, argues that great structures – the Brooklyn Bridge, the skyscrapers of Chicago, the concrete roof-shells of Pier Luigi Nervi – not only overcome technical challenges, but also achieve the status of art. Much is biographical; the achievements of individual structural architects, but the commentary in between is forceful and enlightening.)

Cowan, H.J. and Smith, P.R. (1988) "The Science and Technology of Building Materials," Van Nostrand-Reinhold, New York, NY, USA. ISBN 0-442-21799-4. (A good introduction to materials in architecture, drawing distinctions between structural materials, "externals" or materials for the outside, and "internals" or materials for control of sound, heat and light within the building. There are chapters on stone, steel, wood, concrete, glass and plastics, with guidelines for their selection.)

Duncan, A. (1988) "Art Deco," Thames and Hudson, London, UK. ISBN 0-500-20230-3. (A comprehensive review of the history and characteristics of the Art Deco design movement.)

Fagan, B.M. (1999) "Archaeology – A Brief Introduction," 7th edition, Prentice Hall International, London, UK. ISBN 0-321-04705-2. (An introduction to the methods and techniques of modern archeology.)

Haudrum, J. (1994). "Creating the Basis for Process Selection in the Design Stage," PhD thesis, The Institute of Manufacturing Engineering, Technical University of Denmark. ISBN 87-89867-13-0. (An exploration of process selection, viewed from a design theory perspective.)

Jakobsen, K. (1989) "The Interrelation between Product Shape, Material and Production Method," ICED '89, Harrowgate, August 1993, pp. 775-784. (Jakobsen identifies the interdependence of function, shape, material and process, and that different sequences for selection of the four aspects can be followed.)

Lenau, T. (June 2001) "Material and Process Selection using Product Examples," presented at the Euromat 2001 Conference, Rimini, Italy 10-14 June 2001. (An analysis of the material information needs of industrial designers.)

Muller, W. (2001) "Order and Meaning in Design," Lemma publishers, Utrecht, The Netherlands. ISBN 90-5189-629-8. (Prof. Muller teaches Design in the School of Industrial Design of the Delft Technical University. The book describes the process he has developed for understanding and teaching Industrial Design. It contains many useful insights, some of which we have used in this chapter.)

University of Art and Design Helsinki (1995) "koodi Code," UIAH Books, Helsinki, Finland. ISBN 951-9384-97-9. (A delightful set of examples of the redesign of small domestic products in differing styles.)

Chapter 7

Material Selection



To create a tool for material selection we need to structure the information that has been presented so far. This tool – as described in Chapter 3 – should (a) capture and store material, process, and product information, organizing it in a way that allows rapid retrieval, (b) present the same information in a creative format, and (c) allow browsing, retrieval, and combination of “bits” of information about materials, processes, and the products they create. The first step is that of classification.

Classification and Indexing

Classification is the first step in bringing order into any scientific endeavor. The founders of biology, zoology, and geology were those who created the classification systems. Classification segregates an initially disordered population into groups that in some way have significant similarities. These groups can be further subdivided by seeking finer levels of

similarities within each. The success of the great classification systems relies on the choice of relevant attributes and the judgment of what is “significantly similar.” Mendeléeff’s classification of the elements into the periodic table, Darwin’s classification of the natural life of the Galapagos islands, Linnaeus’s classification of plants – all these not only brought order to their subjects but also suggested the existence of missing members of the populations –

undiscovered elements and species. Not all classifications survive – genetic mapping is even now reconstructing the classifications of biology. But this in no way diminishes the importance of the original classification; it was an essential step in reaching the new structure.

Classification has a key role in design. Design involves choice, and choice from enormous range of ideas and data – among them, the choice of materials and processes. Classification is closely linked to indexing, a central activity for both information retrieval and selection. But to be efficient, the classification and indexing must be adapted to the nature of the population of objects that are to be classified and the purpose of the search. Consider the following example.

An Information Structure for a Bookshop

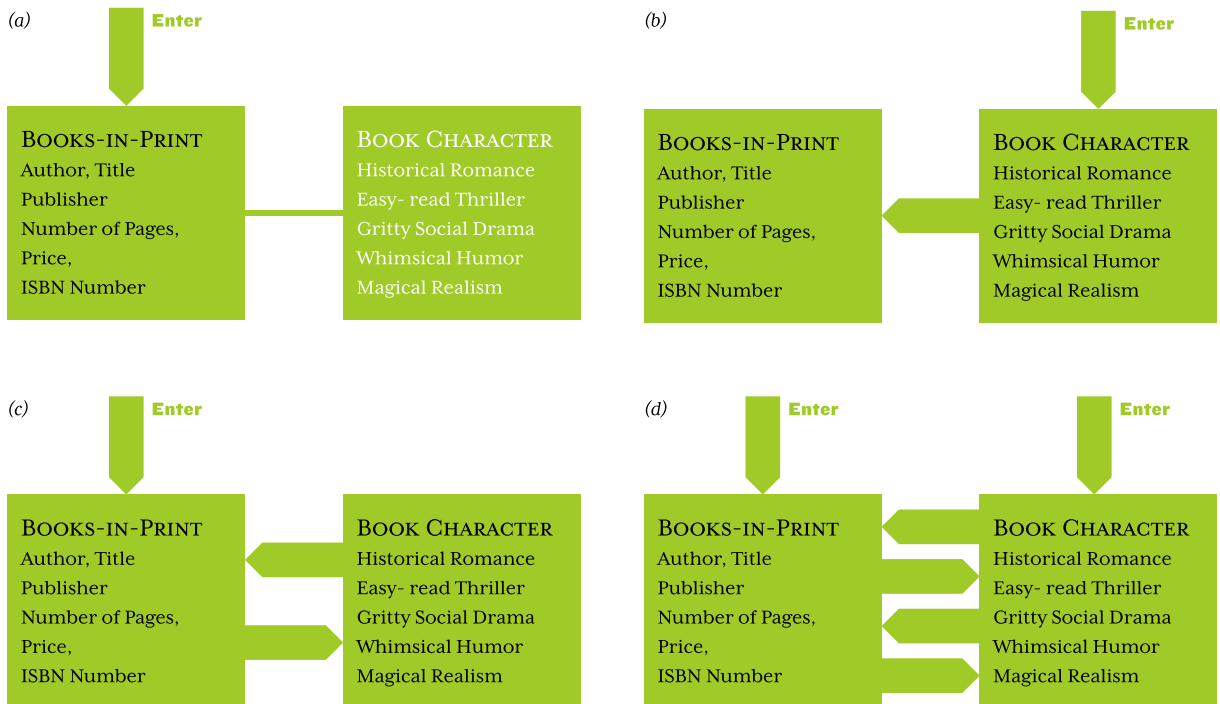
Imagine that you run a small bookshop. You have access to the standard books-in-print database. It lists certain attributes of books: the author, the publisher, title, ISBN number, date of publication, price, and so on. A customer wanting a book and knowing any one of these pieces of information can be helped. The retrieval is objective and systematic: anyone entering the same request will get exactly the same response (7.1a). We will refer to this as “simple indexing.”

But suppose the customer knows none of this and simply wants “a historical romance.” The customer can still be helped if you – the bookshop owner – know the character of your books or have a database that contains such information (7.1b). Here the attributes

describe the nature of the books at a more abstract level: biography, documentary, or fiction; romantic, tragic, or humorous; contemporary or historical, and so on. Now, a search on “romantic and historical” will return books that meet the customer’s wishes. The method is subjective, and is non-systematic – it is based on perceptions, not on simple facts, and views on book character will sometimes differ. But if a broad consensus exists (as with books it certainly does), selection by character is productive: it is fast, flexible, and copes with imprecisely defined inputs. Although it is not exact, it is a big step forward; the alternative is the response “if you don’t know the ISBN number I can’t help you.” We will refer to it as “deep indexing.”

And there is more. Figure 7.1c shows selection of a different sort. Here, the selection is no longer a simple search using the relevant index; it depends on analogy. It is a response to the customer who likes books by author x, but having read them all now wants books with a similar character, written by other authors. The books by author x have one or more abstract characteristics, and these same characteristics are linked back to other authors. And here the precise words used to describe book character are less important, they are, as it were, “dummy variables,” creating associations between one author and another.

Taking this one step further (7.1d), the coupled pair of databases allows “browsing.” Browsing is curiosity-based searching, the way to satisfy a need that is felt but imprecisely defined. It is like wandering through the bookshop pulling books from the shelves and examining



their character until a satisfying combination is found. Browsing allows unplanned suggestion, serendipity: you leave the bookshop with books that – when you entered – you didn’t know you wanted. And that is a sort of inspiration.

This may seem a long way from the central subject of this book, but there are useful messages in it. Here are two. First: the choice of attributes, and the classification and indexing that follows from it, must be adapted to the purpose for which the information will be used. And second: multiple indexing allows a richer diversity of selection methods, among which the most striking distinction is that between those based on analysis – “find an object that has something” – and those using analogy – “find an object that

is like something.” So how are classifications constructed?

- *Empirically* – using verifiable, universal facts – as social scientists might classify the population by age, sex, married status, number of children, profession, income, and the like.
- *Visually* – by seeking clusters in “density-maps” of attributes – as in classifying crime statistics by plotting occurrences on a map of a country and grouping those areas with a given area-density of such occurrences. The methods of attribute-mapping and of multi-dimensional scaling, described in Chapter 4, reveals “similarities” within populations of materials, processes, or products.

7.1 Indexing and Selection

(a) Simple indexing by objective attributes, using “the object has attributes...” (b) Deep indexing by associations or perceptions, using “the object has features...” (c) Selection by synthesis, using analogies – “the object is like...” (d) Selection by inspiration, by browsing...

- Using underlying *scientific knowledge* – as in the classification of materials based on the nature of their interatomic bonds and crystal structures, or of the classification of animals based on their DNA.
- By more abstract qualities of *perception* or *association* – as you might classify friends as sensible, emotional, tolerant, or short-tempered; or as we classified books as thrillers, or romantic novels, or social dramas.

The science-based classification, reinforced by property maps, worked well for the engineering attributes of materials (Chapter 4). The empirical method worked adequately for processes (Chapter 5). But for products we need something more abstract.

An Information Structure for Product Design

Figure 7.2 shows a schematic of an information structure for product design. It draws together many of the ideas developed in earlier chapters. It is made up of six linked data-tables. The central table – products – contains factual data for product attributes: the product name, manufacturer, model number, price, and details of performance. Products can be retrieved by searching on these attributes, just as books can be retrieved by title or ISBN number. It allows simple indexing.

A deeper level of indexing is made possible by linking each product to the

materials and processes used in its manufacture (left-hand side of 7.2). It is now possible to search for all products made, say, of ABS, or of stainless steel, or those decorated, perhaps, by pad printing. And it opens up new ways of selecting materials by analogy and browsing, to which we return in a moment. But first: the tables on the right of 7.2.

The first contains information about product aesthetics: the visual, tactile, acoustic and – if relevant – olfactory attributes listed in 4.21. It allows products to be indexed by these features, and indirectly, through products, it links these features to the materials and processes able to provide them. The second contains information about perceptions – the attributes listed in 4.26. It is like the “book character” table of 7.1. Its content and the links from it to products are matters of judgment: they depend on culture, taste, and fashion, and they evolve with time. But, as argued earlier, the fact that they are imprecise does not mean that they are useless; they allow products to be indexed in new ways and give new paths for retrieving information about materials and processes based on the ways in which they are used.

One table remains – that at the top of 7.2. In designing a product the designer is guided by certain broad priorities that condition, to a greater or lesser degree, all decisions and choices. We encountered these in Chapter 6, where they were called Intentions (6.7). The word “intention” describes what the product is *meant* to be – the priorities in the mind of the designer. Indexing by intentions allows a degree of abstraction, grouping

together products that may differ radically in function but are designed with a similar set of priorities. The intention “Design for the elderly” implies a vision of a product with functionality, appeal, and price that are adapted for old people, influencing choice of configuration, form, size, color, and texture, and of the materials and processes used to achieve them. “Design for mass-production” implies a vision of a product that can be made quickly and cheaply by automated equipment, directing choice of material and process for shaping, joining, and finishing. “Design for recycling” implies a choice of materials and of ways to join and finish them that will enable disassembly and their return into the production cycle. If the intentions are known or can be inferred, products can be linked to them.

It is a complex picture. An analogy will help. Think of the product as a person – anthropomorphize it. Then the left-hand side of 7.2 – the materials and process bit – becomes the flesh and bones, the things you can hold and feel – the physiology of the product. The right-hand side – the aesthetics and perceptions bit – becomes the appeal and character, the product psychology. Finding an analogy for intentions is harder – perhaps it is the characteristics with which, by parentage, the person is endowed. Add them all up and they create the *product personality*.¹

This information structure allows simple indexing of a product by its attributes: name, maker, serial number, and so on. More helpfully, it can be indexed in a deeper way by material, process, intention, aesthetics, and perception.

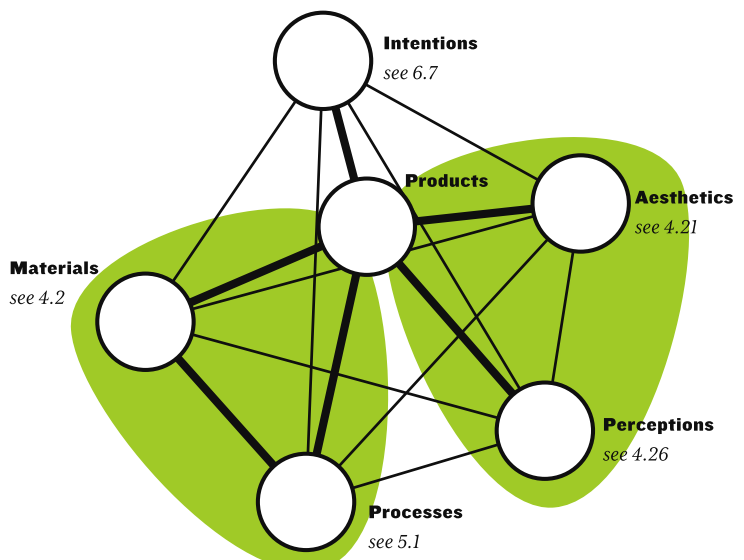
The deeper indexing allows a whole set of selection methods, just as the indexing of books did.

An example will illustrate some of these. The concept: a child’s car seat. The starting point is a design brief, setting out certain requirements and implying a feature list. The seat must hold and protect the child when subjected to decelerations of up to 10g; it must be strong enough to withstand the inertial forces that this demands yet not damage the child while doing so. Its dimensions must allow it to pass through a car door easily. It must be light, yet able to withstand mishandling and impact, and it must be easy to clean. Second, the intentions. There are several: “design for children” is the obvious one, but “design for mass production” and “design for low cost” probably enter too. Focus on the first: design for children. If you think of products for children, you think of robustness and tolerance of

1. Perhaps to be thought of as the “product DNA,” meaning the particular combination of features that distinguish it from all other products.

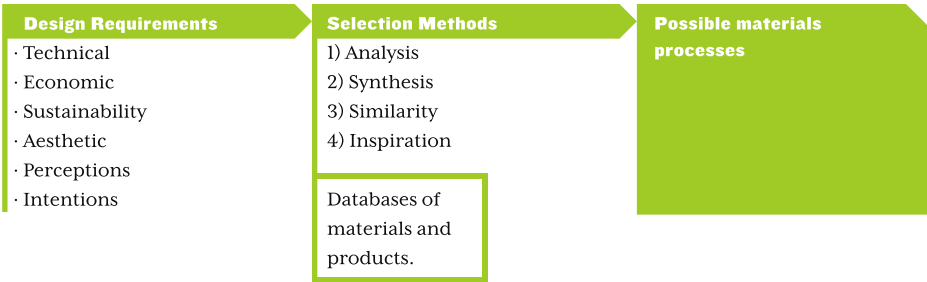
7.2 An Information Structure for Product Design

Each circle and its links is explained in the text. The numbers beside each circle refer to a table in the text.



7.3 Methods of Selection

(1) by analysis; (2) by synthesis; (3) by similarity; and (4) by inspiration.



misuse, of high standards of safety, non-toxic materials, simple, bold forms, and bright colors. What can be learnt from other products that were designed with this intention?

An examination of products which are designed for children can give ideas that might help with the car seat. ABS, PP, and nylon are used in many products for children. They are strong, tough, corrosion resistant and, of course, they are non-toxic and carry FDA approval. All can be brightly colored and – being thermoplastics – are easily molded. This information doesn’t design the child’s car seat, but it does suggest options that are worth exploring and ways of creating the features we want.

The seat must meet certain technical requirements. It must be light and strong, requiring materials with high strength-to-weight characteristics. It

must withstand impact yet deflect when the child is thrown against it, requiring materials that are tough and resilient. The material profiles later in this book characterize toughness and resilience: among polymers, ABS, PP, and nylons are both, as are fiber-reinforced polyesters and epoxies. The material must be capable of being molded or pressed to a complex shell-like form with the necessary fixing points for straps, harnesses, and padding. If the ability to be colored and molded at low cost are priorities, ABS and PP move to the top of the list. If light weight and strength are more important, then fiber-reinforced polymers move up – but they may have to be painted or coated, and children have ways of removing paints and coatings that defeat all known ways of applying them.

Successful product design makes use of all this information, and does it in

7.4 Technical Analysis for a Bicycle Spoke

Constraints, listed in the top three lines, allow screening, eliminating materials incapable of providing the function. The objective of minimizing mass allows those that survive to be ranked.

Inputs	Path to Material Selection
Impact resistant	Fracture toughness, $k_{ic} > 20 \text{ mpa.mH}$
Corrosion resistant	No materials that corrode in water
Available as rod	None that cannot be extruded or drawn
Light and withstand design load	Rank by ratio of strength to density

more than one way. We explore these next, focusing on the selection of materials and processes.

Material Selection for Product Design

Life is full of difficult choices. Everyone has his or her own way of dealing with these, some effective, some not. Studies of problem-solving distinguish two distinct reasoning processes, already touched on in Chapter 3: *deductive* and *inductive* reasoning. They are the basis of selection by analysis, by synthesis, and by similarity, which we now examine in more detail, using the data structure of 7.2.

The act of selection involves converting a set of inputs – the design requirements – into a set of outputs – a list of viable materials and processes (7.3). There are several methods for doing this.

Selection by Analysis²

Technical engineers are trained in analysis – it is one of the tools of the trade. The inputs here are the technical requirements. The analysis proceeds in four steps.

- *Translation* of the requirements, often expressed initially in non-technical terms, into a statement of the objectives and constraints the design must meet.
- *Analysis* of the component for which a material is sought, identifying performance metrics and expressing

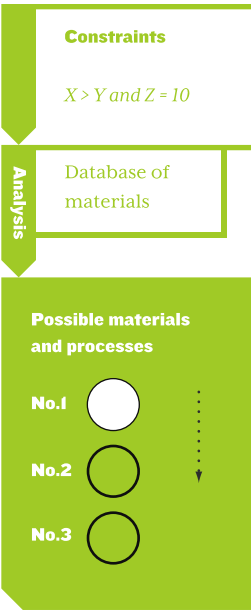
these as equations that measure performance.

- *Identification*, from these equations, of the material properties that determine performance.
- *Screening* of a database of materials and their properties, eliminating those that fail to meet the constraints, and ranking those that remain by their ability to maximize the performance metrics.

Thus – to take a simple example – the choice of a material for the spoke of a lightweight bicycle wheel might proceed in the way shown in 7.4. The first three design requirements impose limits on material attributes, screening out unsuitable candidates. Those that remain are ranked by the fourth requirement – that of strength at minimum mass (here mass is the metric of performance). This must be balanced against cost, using trade-off methods. The method of analysis is summarized in 7.5 and the Appendix to this chapter; it will not be followed further here.

The method of analysis has great strengths. It is systematic. It is based on a deep (“fundamental”) understanding of the underlying phenomena. And it is robust – provided the inputs are precisely defined and the rules on which the modeling is based are sound. This last provision, however, is a serious one. It limits the approach to a subset of well-specified problems and well-established rules. In engineering, as in all other aspects of life, it is sometimes necessary to base

2. A brief summary of the analytical method for selecting materials is given in the Appendix to this chapter. Full explanations are given in texts on material selection such as Dieter (1991), Charles et al. (1997), or Ashby (2012) and Ashby et al (2013); the last of these gives many worked examples.



7.5 Selection by Analysis
Requires the selection of a material from a database of materials and material attributes. Here the white circle represents a solution that meets all the constraints and maximizes the objective.

7.6 Desired Perceptions for an Insulin Pump
Perceptions can be created by combining features from other products that are perceived in a particular way.

decisions on imprecisely specified inputs and imperfectly formulated rules. Then the analytical method breaks down; methods of a different sort are needed.

Selection by Synthesis
Synthesis has its foundations in previous experience and analogy. Here the inputs are design requirements expressed as a set of features describing intentions, aesthetics, and perceptions. The path to material selection exploits knowledge of other solved problems (“product cases”) that have one or more features in common with the new problem, allowing new, potential solutions to be synthesized and tested for their ability to meet the design requirements.

Again, a specific example will help. A manufacturer of medical equipment perceives a need to adapt its insulin pump, at present perceived as clinical and intimidating, to make it more acceptable – friendly, trendy, even humorous. This leads to a list of desired perceptions listed in 7.6. A starting point is a search for other products that are perceived in this way. A search on “trendy” and “humorous” gives a number of products that are characterized by bright colors, the use of transparent

polycarbonate and translucent polypropylene and polyethylene, soft overmolded elastomers, simple rounded shapes sometimes with reference to human or animal forms, often made by injection molding. These suggest changes in design that the company may wish to pursue.

At first sight the analogy-based methods of synthesis (7.7) appear to have one major drawback: because they depend on past experience and designs, they cannot suggest radically new solutions, whereas analysis, requiring no such inputs, can. This, however, may be too harsh a judgment. The method encourages cross-pollination: developments in one field can be adapted for use in another where it was previously unknown; it is innovation of a different sort – what might be called *technology coupling*.

Selection by Similarity
There are many reasons why a designer may wish to consider similar materials: the need for substitution, breaking preconceptions or simple exploration. What is the best way to find them? Substitutes are sought when an established material ceases to be available or fails, for some reason, to meet a changed design

Inputs	Path to Material Selection
Trendy	Translucent, brightly-colored plastics Fabric or wood laminates
Humorous	Soft overmolded elastomer surfaces Bright colors and simple shapes Injection molded or laser etched details

requirement – because of new environmental legislation, for example. Analysis – the modeling of function, objective and constraints from scratch – may be possible, but in doing this we are throwing away valuable information. Established materials have a respected status because, for reasons that are not always fully understood, they have the right complex mix of attributes to meet the requirements of the design. The attribute profile of the incumbent is, as it were, a portrait of an ideal. A good portrait can capture much that is subtle and hard to analyze.

The substitute, ideally, should match the incumbent in all important respects except, of course, the reason for wishing to replace it. So one way to approach such problems is that of “capture-edit-search.” First, capture the attribute profile of the incumbent – easy, with present-day data sources. If we use this as a template for selection we will probably retrieve only the material we started with. So the next step – edit – involves relaxing the constraints on non-critical attributes, admitting a wider range of candidates and tightening the constraint on the one attribute that was causing the problem. The last step – search – retrieves substitutes that offer the essential qualities of the incumbent, without its weaknesses (7.8).

A search for similar materials can serve as a method of expanding the set of possible material solutions. Designers often have pre-conceptions: that polycarbonate, ABS, or a blend of the two are the best choices for product bodies and shells; that polyethylene, polypropylene,

or PET can solve most packaging problems; or that aluminum or steel are the answer for most “engineering” products. Pre-conceptions may be a shortcut to a quick solution but they constrain innovation. A search for similar materials can break pre-conceptions and thereby introduce creativity or novelty in a design solution.

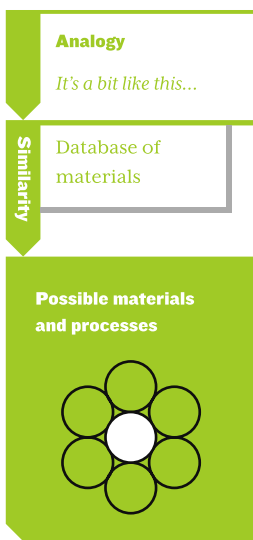
Selection by Inspiration

Designers get most of their ideas from other designers (past as well as present) and from their environment. It is possible to search for these ideas in a systematic way – that is the basis of selection by synthesis. It relies on a mental index (or indexed books or computer files) to search for features and the way they are created. But many good ideas are triggered by accident – by an unplanned encounter. The encounter is “inspiring,” meaning that it provokes creative thinking. The scientific method is of no help here; inspiration of this sort comes by immersion; by exploring ideas almost at random, like delving in a treasure chest (7.9). The word “almost” here is important; if inspiration is to be useful, the treasury of ideas needs to have a little structure. Inspiration can be gained by interaction with materials, through a material collection or – less good – through images of them. It can be gained by interaction with products, by browsing in stores that market good design, or by browsing in books – indeed, one role of ID magazines and coffee-table books is simply that of presenting the reader with provocative images in more or less random order.



7.7 Selection by Synthesis

New solutions are generated (and materials for them selected) by examining existing products with features like those required for the new design. Here the white circle represents a synthesis of features from the three solutions (colored circles) it contains.



7.8 Selection by Similarity

Finding substitutes by matching attributes profiles. Here the colored circles represent materials that have values of critical attributes that match, as nearly as possible, those of the established material (white circle).

Combining the Methods

Figure 7.10 shows a way of thinking about all these methods. It is a development of the bubble model in Chapter 3, specialized to the selection of materials and processes. In it, the selection methods we have just described are seen as large bubbles; their job is to generate possible solutions for the design brief. Each generates a population of little bubbles – the solutions that have survived or emerged from the technique, each containing information about a material or a material combination. The selection methods – the larger bubbles – draw on two major resources: a database of materials and processes, and a database of products, stored as “cases”: indexed examples of the use of materials in products.

The choice of path from design brief to product specification depends on the nature of the selection problem. If well specified, the method of analysis efficiently screens the population contained in the database of materials, killing off members that cannot meet the requirements and ranking those that can by a measure of their performance, giving the possible solution “bubbles” 1, 2, 3.... The database of products then provides supporting information – products in which these selected materials have been used.

If the requirements cannot be easily quantified, analysis is disabled. The method of synthesis can be used to generate possible solutions such as A, B, C... by exploring products that have the desired features, extracting material and process information about them. Here

the database of products is the principal resource; that of materials simply provides the data profile once a possible material solution has been found. When the specification is even less precise, possible solutions a, b, c... can still be generated by using the method of similarity – that of seeking materials with profiles like that of the one already used – indeed, in reassessing material use in any product it's helpful to know what the alternatives are. Here the databases of materials and products both act as resources. Finally a possible solution can emerge from a process of browsing – simply exploring the use of materials in products, chosen at random, using the findings as a source of inspiration (α , β , γ ...).

Any one of these methods can be used in isolation, but the most effective path exploits the most useful features of each. Thus the choice of a material for a lightweight space frame is a well-specified problem, lending itself to analysis and generating possible solutions. But if one of these is unfamiliar, the designer may be reluctant to use it, fearing unexpected problems. Then it is helpful to turn to synthesis, seeking products that are space frames to see what they are made of, or products made of the unfamiliar material. The result of this can be thought of as a merging of solution bubbles from analysis with those from synthesis, generating new, hybrid, solutions. Solutions from the other methods can be combined in a similar way.

As a model for the material selection process, this bubble diagram, though complex and fuzzy, is a more accurate

representation than that of the linear model of 3.3. Within one method – analysis for instance – a linear path may be found but it is rare this leads to an unambiguous choice. Almost always, a more devious path like the one just described is the best. The case studies that follow will illustrate this.

Material Selection

Creative solutions to design problems can be reached in more than one way; the more flexible the approach, the greater the likelihood of creativity. The essential requirements are:

- An *information structure* that allows both simple and deep indexing; here we have cross-indexed by Intentions, Products, Materials, Processes, Aesthetics, and Perceptions.³
- *Selection methods* that can cope both with precisely formulated design requirements and rules, and with less precisely specified features that can include the technical, aesthetic, and perceived dimensions.

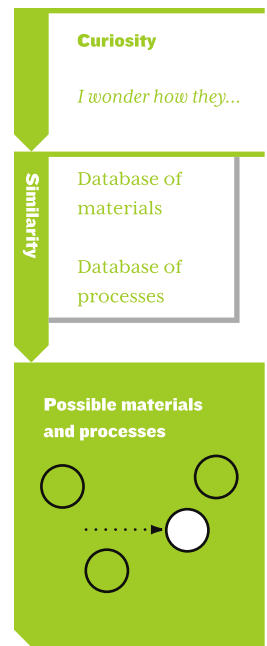
Four complementary methods are described and illustrated here:

- *Selection by analysis* (deductive reasoning), using precisely specified inputs and the well-established design methods of modern engineering, drawing on databases of materials and their attributes.
- *Selection by synthesis* (inductive reasoning), drawing on past

experience, retrieved by seeking a match between the desired features, intentions, perception, or aesthetics and those of documented design solutions, stored in a database of product “cases.”

- *Selection by similarity*, seeking materials with selected attributes that match those of an existing material, without knowing why these have the values they do, merely that they are relevant for the success of the design.
- *Selection by inspiration* – looking for ideas by randomly viewing images of products or materials (or, by visiting stores, viewing the products, and materials themselves), until one or more are found that suggest solutions to the present challenge.

Traditional engineering education emphasizes analytical methods, often to the exclusion of ideas about analogy and synthesis. The justification is that analysis is an exceedingly powerful tool, and one that with modern computer support can be applied with ever greater speed and rigor; further, it can be taught as a set of formal procedures. But there is evidence that many of the most creative ideas in technical fields – science and engineering among them – arise not from analysis but from inductive thinking: from successive guessed solutions (informed guesses, of course, drawing on past experience), testing one after another until a solution, created by pulling together strands from many past solutions, is found that matches the requirements.



7.9 Selection by Inspiration

Inspiration can be sparked by materials or processes, particularly if new or used in unusual ways. Here the circles represent solutions inspired by a random walk through a collection or catalog of materials and products.

3. This structure may be stored in the mind of the designer – the “experience” of a lifetime of designing – but this is of little help to someone new to the field. For them a computer-based equivalent, storing information about products, materials, and processes, indexed in the way described in this chapter, can help.

Each of the methods, then, has its strengths and weaknesses. The one that is best suited for one problem may not suit another – all are needed. Often, the best solution is found by combining all three; this combination, as illustrated here, is a much more powerful tool than any one used alone.

This final method (7.10) is the closest to reality in the context of product design. It is the combination of a little bit of analysis, a little bit of synthesis, a

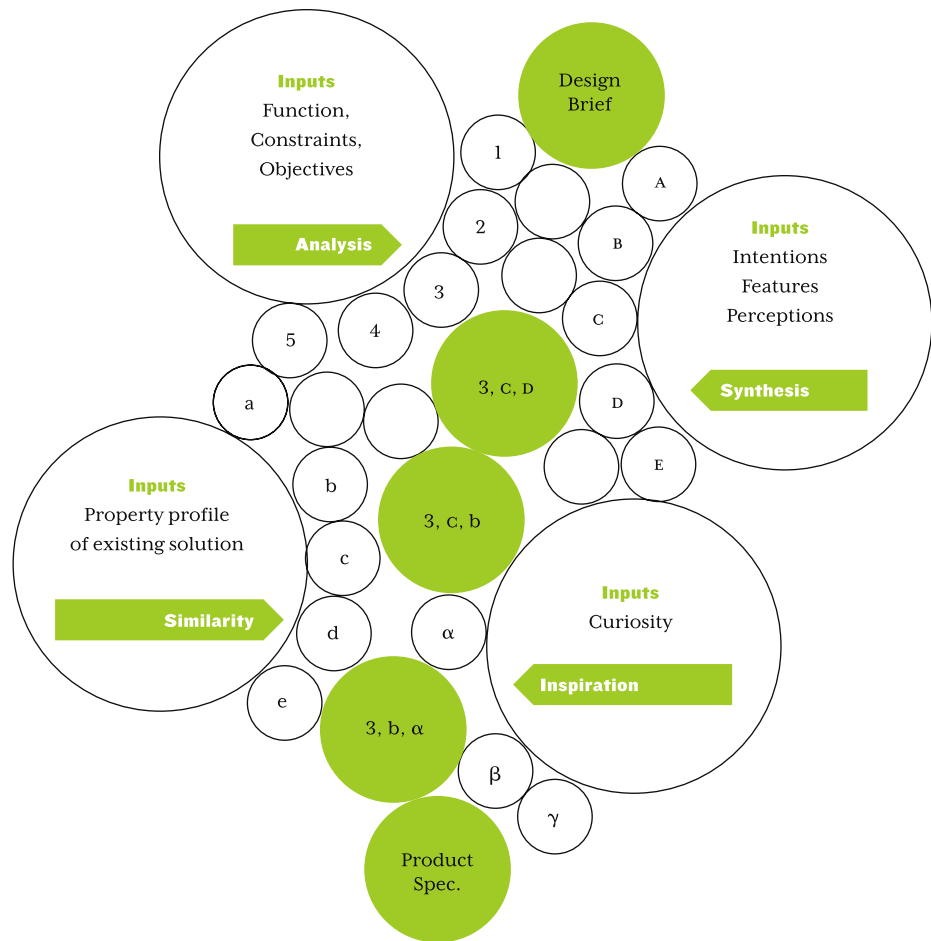
search based on similar products, and broad inspiration from existing material solutions.

Case Studies

The preceding chapters have explored the attributes of materials and processes, and the ways in which this information can be classified and retrieved. Here we turn from exploration to example:

7.10 The Path of Material Selection

Selection is seen as a journey from the design brief to the product specification. The traveler is assisted, in varying degrees, by the tools of analysis, synthesis, similarity, and inspiration (large circles), generating successively refined solutions as the journey proceeds.



how is this information used? The case studies developed in this chapter are necessarily brief. They are designed to illustrate each of the broad methods of selection: analysis, synthesis, similarity, and inspiration

The Structure

Each material selection challenge has its own special features – is, in some way, unique – so there is no single prescription for how to tackle it. It is helpful, nonetheless, to have some structure. The structure follows that introduced in Chapter 7: the starting point is the design brief; the endpoint, a product specification. Between these lie the steps of *identification*, *selection*, and *implications*.

Identification

The first requirement in material selection is a broad understanding of the context. What does the product or the component do? Of what system is it a part? In what environment will it operate? What forces must it carry? What are the consumer's pre-conceptions and expectations? The answers to these questions set the scene within which a solution must be sought. The first priority is to identify the design requirements. Some can be stated explicitly. Constraints, it will be remembered, are conditions that must be met: technical, environmental, aesthetic. Objectives are a statement of what should be maximized or minimized: minimizing cost is an objective; minimizing mass is another; maximizing safety might be a third.

Many requirements cannot be expressed in this way; they are described instead as features, intentions, or perceptions. The nature of these inputs guides the choice of method for selection.

Material Selection

When the objectives and constraints can be expressed as well-defined limits on material properties or as material indices, systematic selection by analysis is possible. When constraints are qualitative, solutions are synthesized by exploring other products with similar features, identifying the materials and processes used to make them. When alternatives are sought for an existing material and little further is known, the method of similarity – seeking material with attributes that match those of the target material – is a way forward. And many good ideas surface when browsing. Combining the methods gives more information, clearer insight, and more confidence in the solutions.

Implications

We now have a set of selected possibilities. The next step is to scrutinize the more intimate aspects of their character; to search for details of how they are best shaped, joined, and surfaced; to establish what they are likely to cost, how long they will last, and how they respond to particular environments. How well does the list of possible solutions meet the original design brief? Does its use carry other implications – environmental impact, perhaps, or the need for the introduction of a new manufacturing process?

7.II Selection by Analysis

For office furniture, selection by analysis requires the optimization of a set of objectives given a set of constraints.

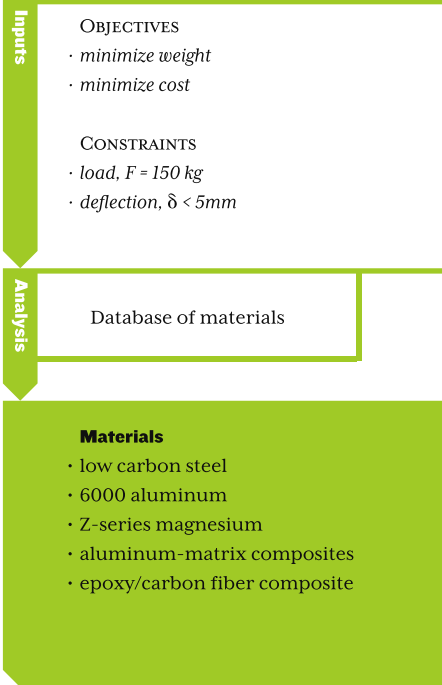
The case studies follow this general pattern. They omit much detail, and simply aim to show how the methods combine and reinforce each other (7.10), sometimes drawing more from one, sometimes from another, but blending to achieve more than is possible by any one alone.

Office Furniture

A manufacturer of steel-framed office furniture wishes to launch a new line of tables that are lighter and easier to move. An office table, designed for mass production, has a frame supporting a work-surface. It must be light and cheap, yet support normal working loads safely – and this includes the load of a large person sitting on it – without failing or deflecting significantly (7.11). The current design has a frame made from square-section mild steel tubing, welded at the joints. There is a belief on the part of the client that a potential exists for using extrusions of a lighter metal. This throws up questions of material, joining and shape for stiffness at low weight, and ease of assembly. It is a problem that lends itself both to analysis and to synthesis; combining the two gives even greater insight.

Material Selection – Analysis

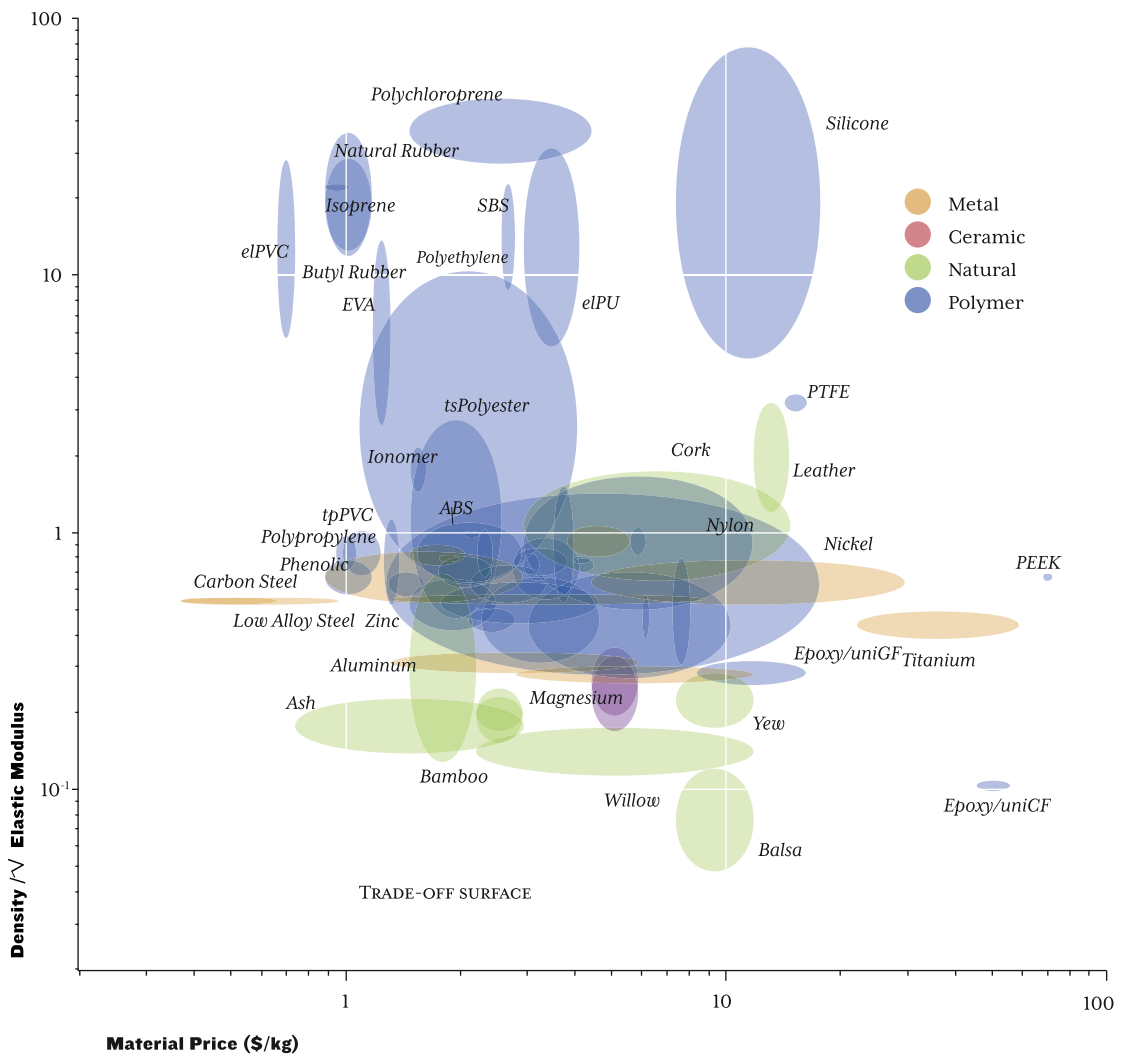
A light, stiff frame, loaded in bending (as this frame is) is best made of a material with a low value of $\rho/E^{1/2}$ (see Appendix) where ρ is the material density and E its modulus. This group of properties characterizes the weight of the frame.



Cost, obviously, is a consideration. The material index $\rho/E^{1/2}$ is plotted against material price/kg in 7.12, on to which a trade-off surface has been sketched. Materials on or near this surface offer the best combination of low weight and low cost. The incumbent material – carbon steel – is marked. It is low in cost but it is also relatively heavy. Aluminum alloys, easily extruded to square section tube, are more expensive, but considerably lighter. Magnesium alloys allow a further reduction in weight, but at a considerable increase in price. Lighter still are GFRP and, particularly, CFRP – but CFRP is expensive.

Material Selection – Synthesis

What can be learnt from synthesis (7.13)? The intention here is lightweight design. Where else do you find lightweight space



frames? Car manufacturers, today, strive for light weight, and achieve it by building the car round a light, stiff space frame. Design for backpacking has, as one of its primary priorities, low weight: backpacks, tents, mountain climbing, and rescue equipment all have lightweight frames, here seeking strength rather than stiffness. And weight car-

ries heavy penalties in other sports: the design of the frames of bicycles and of snowshoes is guided by minimizing mass.

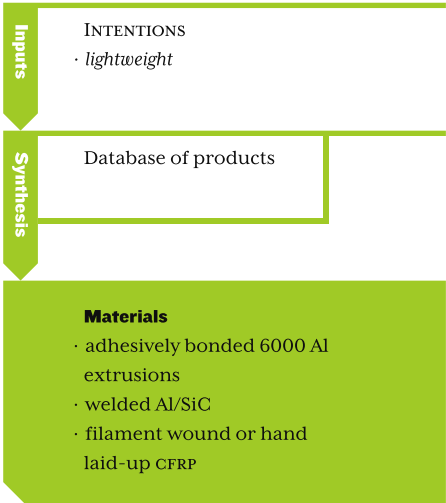
A survey of materials and processes used in these products can suggest options for the desk. Both Audi and Lotus use extruded 6000 series aluminum, welded or adhesively bonded, and riveted, to create light space

7.12 The Trade-Off

Reading a compromise between low weight and low cost (CES Edu, 2009).

7.13 Selection by Synthesis

Here we seek products that contain eight weight space frames, enquiring for the material and process by which they are made.



several lightweight models use tubing made of the 6000/7000 series aluminum or of aluminum matrix composites. High performance backpacks and bicycles are made of carbon fiber-reinforced polyester or epoxy, either as tubing (but this is inefficient) or as a shell made, usually, by hand lay-up of woven prepreg. None use magnesium.

The first three of these are mass-produced products that command substantial market; they boost confidence that 6000 series aluminum holds no unpleasant surprises, and point to ways in which they can be joined (welding and adhesives) and finished (powder coated). This would be the safe choice – one already used in other, similar, designs. The small additional weight saving offered by the aluminum matrix composites does not justify its cost.

frames for cars. Backpacks and snowshoes, too, use 6000 series aluminum tubing, bent, welded, and finished by powder coating. Bicycle frames have been made of many different materials;

7.14 Mobile Office Furniture

With carbon fiber/epoxy composites, a stiff, light table can be formed.



But could there be a more radical solution? CFRP bicycles use lay-up methods to create elegant, doubly-curved shapes; chairs exist that do the same. A high-end desk could be made in a similar way (7.14), molding-in attachment points for drawers and other fixtures as they are on the bicycle. That level of sophistication may not be justified here. But the lightness and stiffness of polymer-matrix composites is an attraction. Pultrusion is a relatively low-cost way of making high stiffness hollow sections of composites. These can be adhesively bonded using cast aluminum nodes at the corners, a technique used in some CFRP bicycles, to form a frame. There is potential here for major weight savings, coupled with novel visual appearance (black CFRP pultrusions with polished aluminum connections) that might be manipulated to give perceptions of advance precision engineering.

CD Cases

We take many everyday products for granted. They work reasonably well, they are easy to use, and they cost next to nothing – think of disposable cups, document folders, and paperclips. Because we take them for granted, we don't value them – and, to some degree, this lack-of-value transfers to their function or contents. And if, for any reason, they *don't* work well, they become a major irritation. CD cases are an example.

Most music CDs are marketed in the standard “jewel” case. Jewel cases crack easily, and when cracked, they look awful

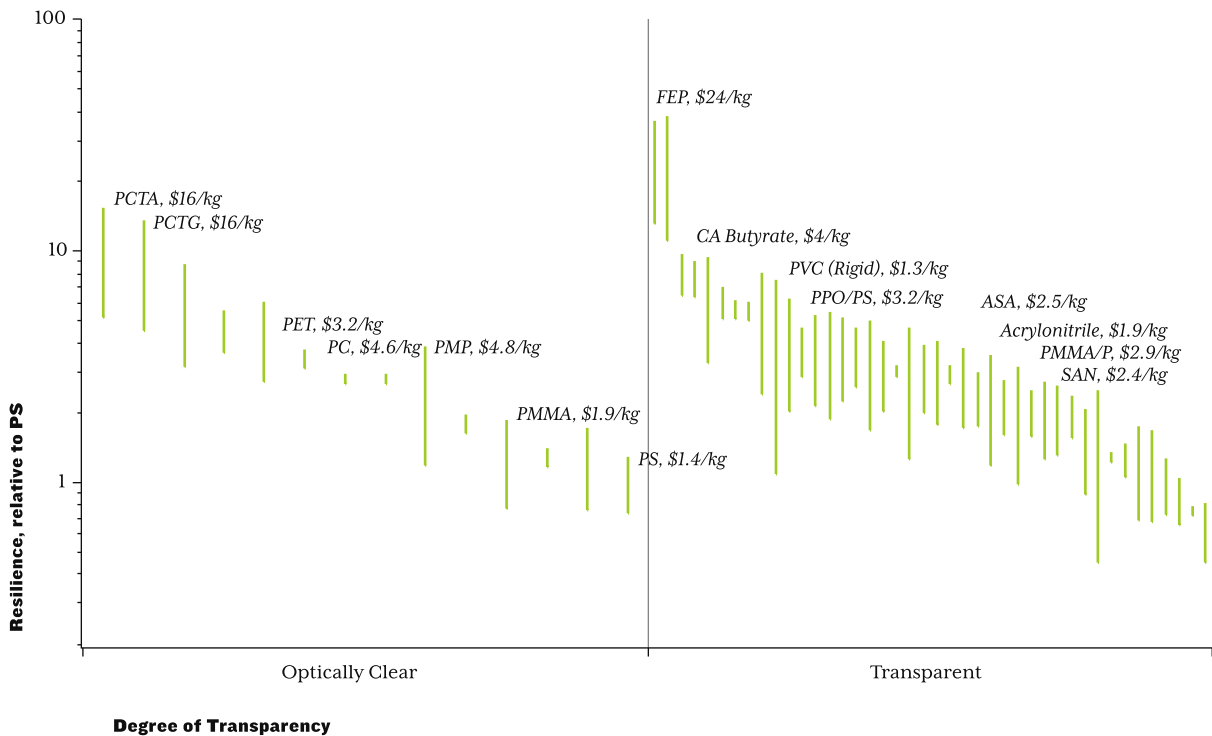
and don't close properly. The standard case is made from polystyrene, chosen, apparently, for its low cost and water-clear transparency. The challenge is to make a case that does not crack and is – if possible – just as transparent.

Material Selection – Analysis

A material cracks when the force put on it makes small imperfections (always present) suddenly propagate. Sharp changes of section and thin projections (as at the hinges of a CD case) concentrate stress and make things worse. The resistance of a hinge to failure by cracking is measured in more than one way. Here the measure we need is the *resilience* – it measures the amount the material can be bent before it breaks.⁴ Figure 7.15 shows this measure normalized by that for the incumbent – polystyrene, PS – meaning that PS lies at the value 1; the scale then shows how much better or worse the other candidates are. Each bar describes a material, labeled with its name and approximate cost. All meet the constraints that they are optically clear or transparent, and can be injection molded. Those with the price below \$4/kg (three times that of PS) are listed in order of increasing cost in the output box of Figure 7.16.

This analysis highlights both the attraction and weakness of the incumbent PS: it is optically clear, moldable, and cheap, but it is also the least resilient of all the clear polymers. A number of materials offer greater resistance to cracking, though – with the exception of PET and PC – it is with some loss of optical clarity. Among these PET

4. The details of this analysis can be found in the Appendix and Ashby (2012); the property used here for resilience is K_{IC}/E where K_{IC} is the fracture toughness and E is the elastic modulus.



7.15 Resilience and Transparency

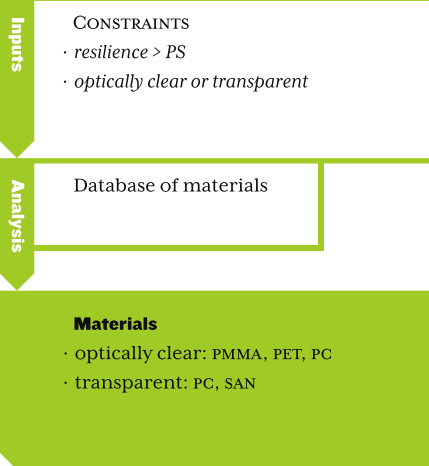
The resistance of materials to breaking when bent is plotted here, relative to that of polystyrene, PS. All the materials shown here can be injection molded and are optically clear or transparent (CES Edu, 2009).

seems to be a good compromise, offering three times the cracking resistance with a modest increase in price. Among transparent (less clear) polymers, SAN is also cheap (and is sometimes used for CD cases) but it, too, is relatively brittle. PVC is an interesting possibility: it is cheap, has high resilience, and could allow a design with a “living hinge” or integral joint, replacing the troublesome pin-joint of the jewel case. Its lack of clarity means that CD labeling will have to be printed or adhesively bonded onto the outside of the case or the case designed so that the entire label on the CD itself is not covered. The proposed solution: a PVC living hinge design, with cut-outs to expose the printed side of the CD,

and with adhesively applied labeling if needed (7.17).

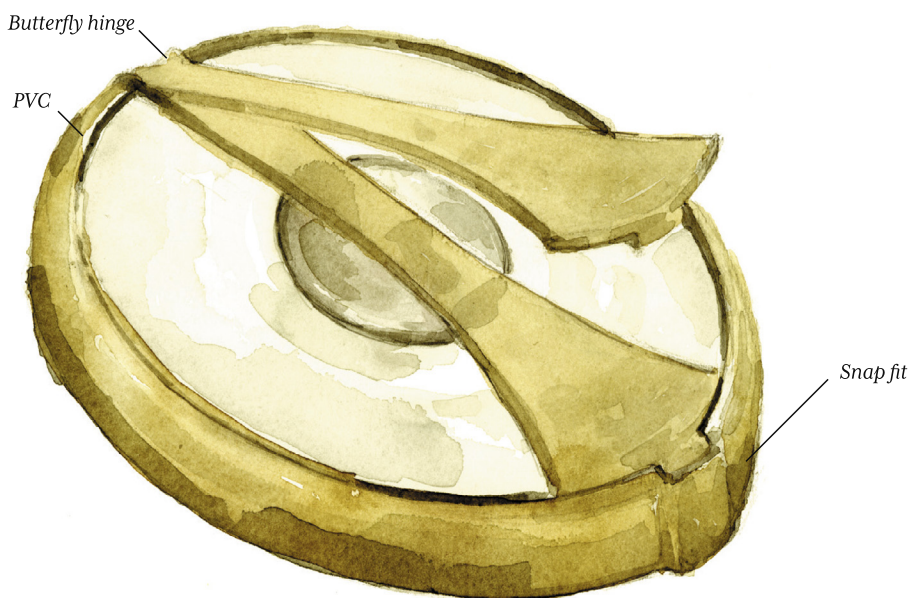
Inspiration could be sought in other ways, provoking other lines of thinking. Product reviewers in design magazines use such words as “cool,” “trendy,” “futuristic” when they feel that the product they are reviewing justifies them. How about a CD case that evokes these perceptions? A search in recent issues of design magazines (like *ID* magazine) turns up products about which these words were used and identifies the materials used to make them: handbags – translucent polypropylene in iridescent colors; lighting – opalized translucent polycarbonate (rather expensive for a CD case); furniture – beaten aluminum

sheet joined by riveting (a bit much for a CD); backpacks – nylon fabric reinforced with polymer tubing (but too floppy to protect the CD). All at first sight rather unpromising. But not so fast – there are ideas here. Some grades of polypropylene are nearly transparent, certainly translucent, and they can be colored and are easy to mold – those qualities of the handbags could be captured here. Acrylic (PMMA), too, can be colored and molded, and it can be metallized – the robust metallic look of the riveted aluminum could be simulated in this way (as it is in the cases of many small cameras). The appeal of the nylon fabric lay in its texture – that, too, could be simulated by printing. Browsing in this way liberates the imagination, allowing jumps of concept not possible by analysis alone.



Violin Bows

When an established material that fits its function well can no longer be used, a need arises for a substitute. This might



7.16 Selection by Analysis

For a CD case, the constraints on analysis are resilience and transparency.

7.17 A CD Case

This case (perhaps of PVC) has an open design allowing a line of sight to the label on the CD. The closure has a "butterfly" living hinge, giving positive closure and opening, and allowing single part molding.

5. Wegst, U.G.K. (1996) PhD thesis, Engineering Department, Cambridge University, Cambridge, UK.

6. A similar predicament threatens the use of Honduras mahogany for electric guitars.

7. Handbooks such as the "Handbook of Wood and Wood-based Materials" of the US Forest Product Laboratory, Forest Service, US Department of Agriculture tabulate wood properties (Hemisphere Publishing Corp, New York, 1989).

8. CES Edu, 2009, Granta Design, Cambridge (www.grantadesign.com).

7.18 A Violin Bow

Bows are traditionally made of pernambuco with little variation in the design.

be because the incumbent material has become too expensive; or that its availability is for some reason restricted; or that it was environmentally damaging; or that it was being exploited at a rate that was unsustainable. Any one of these can disallow its use, killing an otherwise near-perfect application of a material. The following case study is an example.⁵

Violin bows (7.18) are, by long tradition, made from a single species of tropical hardwood: pernambuco. But pernambuco is slow growing and with limited habitat. Violins, requiring bows, are made in large numbers. As a result, pernambuco is dangerously over exploited; there is a real possibility it may become commercially extinct.⁶ Is there an alternative?

Material Selection – Similarity

The physical principles underlying certain uses of materials can be hard to unravel, and this is one. The bow performs several functions. It acts as a spring, keeping the hair under tension, so its stiffness is important; in seeking a substitute we must match this stiffness, requiring a material with a flexural modulus in the range 9.5–11.6 Gpa. The bow mass, too, is important: the lowest bow forces are achieved by using the weight of the bow alone, so here we seek

to match pernambuco with a material of similar density: about 900 kg/m³. There are other constraints: strength is obviously one; bows do split but it seems pernambuco copes with this adequately. And one might anticipate that the mechanical damping (measured by the loss coefficient) might be important: a low loss bow may allow crisper bowing techniques but, of course, natural frequencies are more easily excited in a poorly damped structure. The answer is to match the damping of pernambuco. The input box of 8.9 summarizes the required match.

Here the strategy is a simple one: simply seek materials with values of these four critical properties that lie within the given ranges; then examine these, seeking those that are not threatened by extinction. The results, easily retrieved via a search of wood handbooks⁷ or with current selection software,⁸ are listed in the output box of Figure 7.19. Interestingly, all are woods; no other class of materials offers this combination of attributes.

But perhaps we are being too hasty. We don't really know that density, modulus, strength, and loss coefficient determine bow performance; all we really know is that the bow performs a mechanical function. It is worth trying a match of a

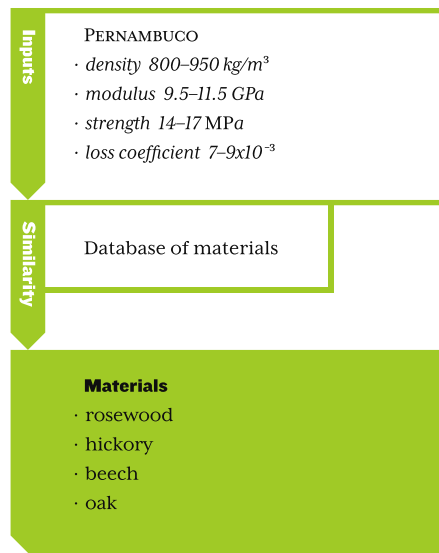


looser kind, one that uses all the mechanical properties in the form of an MDS map (4.5). Seeking a substitute for the bow material by proximity on this map gives – as expected – other woods; but it also suggests that carbon or glass fiber-reinforced polymers (such as bulk molding compound) are, in a general way, similar.

So there are alternatives, all widely available and easily sustained. All, it turns out, have been tried at one time or another. But despite this good match, the overwhelming preference remains that for pernambuco. Why?

Some obvious questions remain unanswered. How well can the alternative woods be bent over heat? How well do they retain their curvature? How easily are they worked? And how regular is their growth? How does a bow of BMC perform? The way to find out is to make trial bows from these candidates and test them – and this, as already said, has been done with apparent success. Why, then, are the substitutes resisted?

Materials for musical instruments are chosen not only for mechanical and acoustic behaviors but also for reasons of tradition and aesthetics; a wood that is unfamiliar in color or texture is “wrong,” purely for those reasons. So we are brought back to the attributes of perception. Perceptions influence choice, and particularly so in a market as strongly traditional as violin-making. The only way forward is one of persuasion – perhaps achieved by inducing great players to use and commend the new bow, encouraging others to perceive it in a new, more desirable, light.



7.19 Selection by Similarity

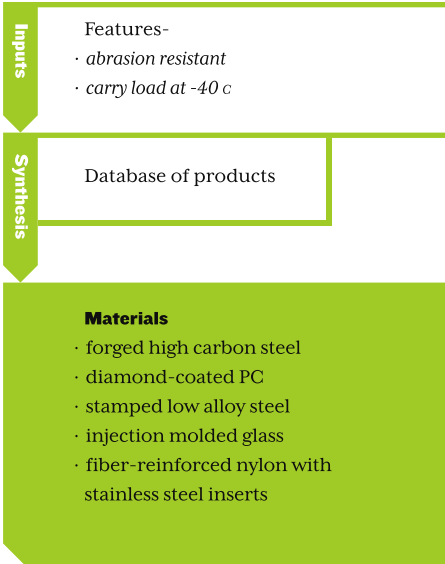
For the violin, there are very few synthetic materials with a matching profile of attributes.

Ice Axes

Mountain climbing equipment serves two primary markets – industrial climbing (the construction industry) and recreational climbing (mountains, rocks, glaciers). The gear is specialized: ropes, harnesses, karabiners, rock screws, backpacks, tents – and ice axes. The focus here is on ice axes for recreational climbing. Ice axes date from the time when climbing first became a recreation – around 1870 – evolving from tools used by the Alpine peasant. Early axes had iron heads and shafts made of hickory, ash, or bamboo. Modern axes have heads made of low alloy (Cr-Mo) steel, with aluminum alloy shafts encased in polymer grips. This combination works, but are there alternatives? Could something be learnt from other products that might lead to a better axe?

7.20 Selection by Synthesis

For ice axes, synthesis of related products requires access to a database of products and materials that make them.



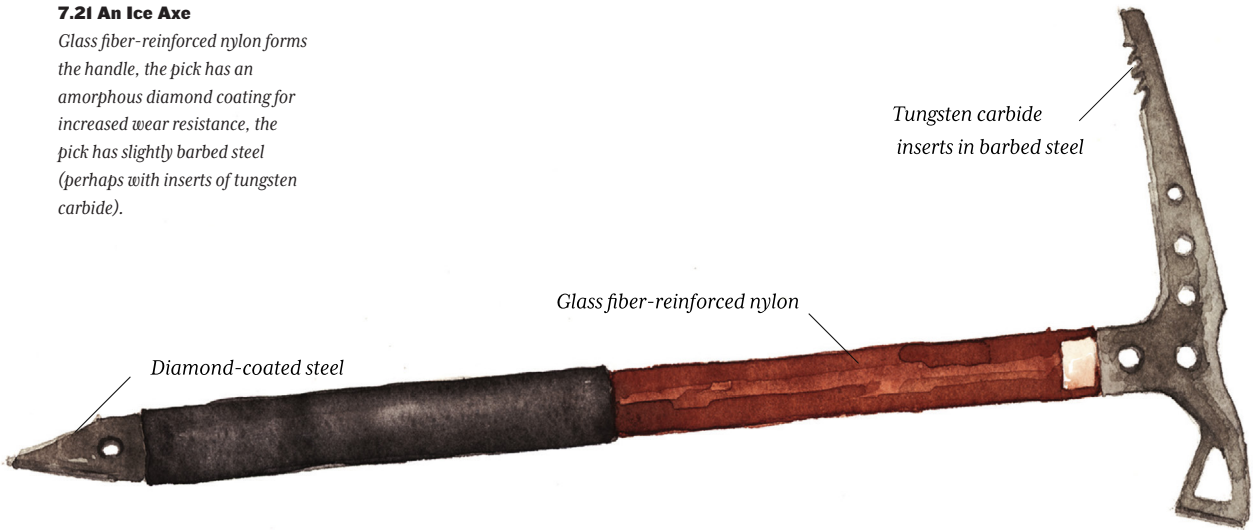
Material Selection – Synthesis

The requirements for the head are resistance to abrasion and wear, to brittleness when cold, and the ability to take a high polish and a discretely textured manufacturer's logo. Those for the handle are strength, low weight, low thermal conductivity, and a good grip. Here we seek

ideas drawn from other products that meet similar constraints, even though the application may be quite different; particularly those that are designed for use at low temperatures: ice hockey skates, figure skate blades, fish hooks, crampons, hiking boots, sunglasses. The ice hockey skate has a stainless steel blade that is molded into a nylon/glass fiber composite sole. The figure skate blade and the fish hooks are both made of high carbon steel that has been hardened by deformation itself (forging for the hook, or stamping for the blade) and by subsequent heat treatment. The crampon is made of low alloy steel that has been stamped and bent. The harness that holds the crampon to the hiking boot is made of a polyurethane-coated fabric. The sunglasses are injection molded polycarbonate with a diamond-like coating to protect the lenses from abrasion. Selection by synthesis proceeds by choosing elements from among these that have possibilities in the design of an

7.21 An Ice Axe

Glass fiber-reinforced nylon forms the handle, the pick has an amorphous diamond coating for increased wear resistance, the pick has slightly barbed steel (perhaps with inserts of tungsten carbide).



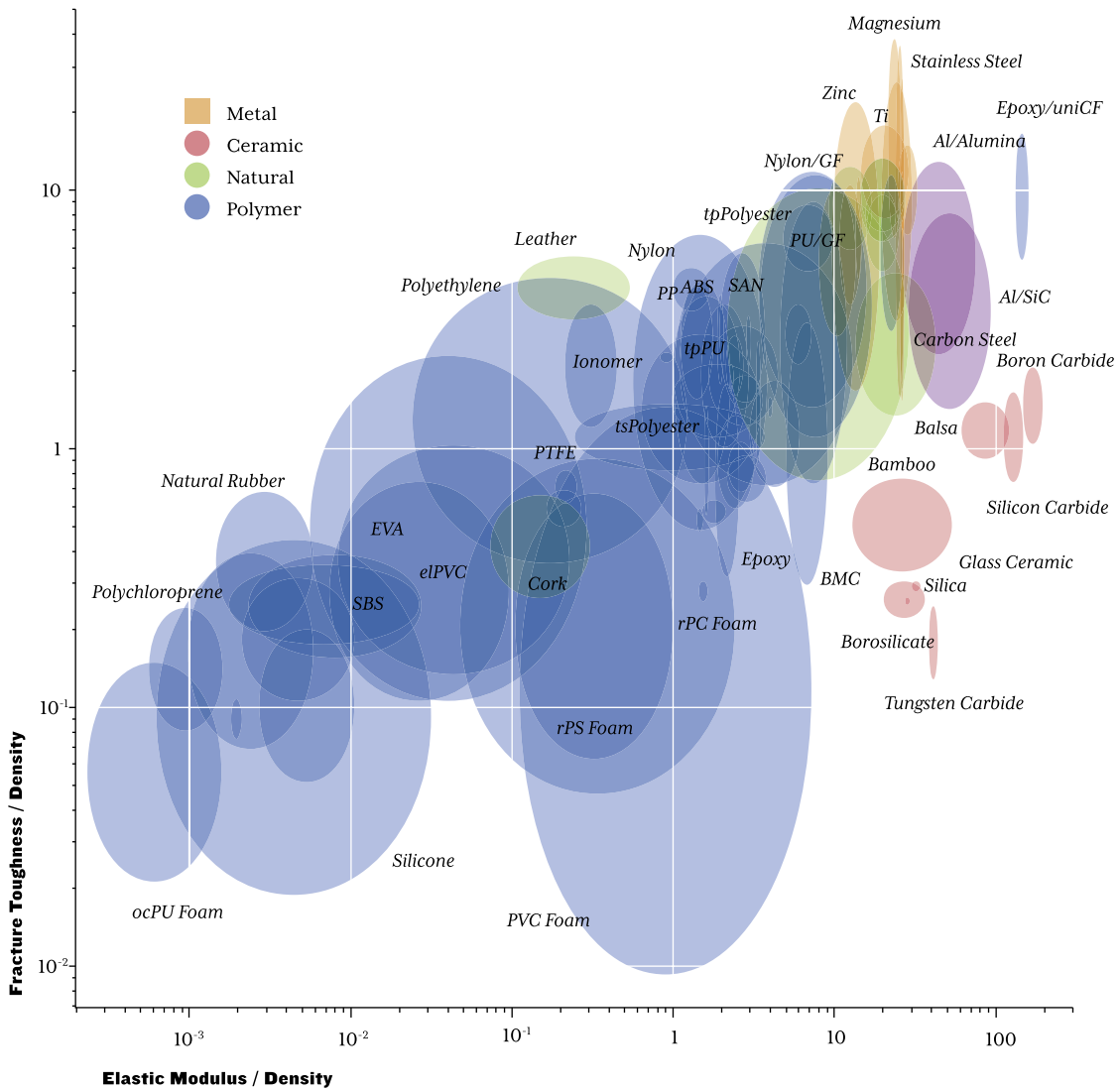
ice axe, combining them to give a final product specification (7.20).

The ductile-to-brittle transition temperature of carbon steel can lie above -30°C ; it is adequate for fish hooks and figure skates that rarely cool below -4°C , but risky for an ice axe that might be used at much lower temperatures. Both stain-

less steels and low alloy steels meet the toughness requirement; of the two, the low alloy steel is stronger. There is no case here for a change of material for the head, but certain design features such as the barb of the hook or the teeth of the skate might be used to give the axe greater grip in dense snow. The end pick of an ice

7.22 Impact Resistance and Stiffness at Low Weight

Inline skates balance the constraints of impact resistance and stiffness – both at low weight and with similar behavior to nylon or PE (CES Edu, 2009).



axe must stay sharp even under severe abrasion; here a ceramic or diamond-like carbon coating like that of the sunglasses could improve performance. The handle offers greater scope for innovation: the use of glass fiber-reinforced nylon offers the possibility of lower weight and much lower thermal conductivity – an important consideration when it must be gripped in the hand; and the addition of a soft polyurethane coating could help ensure that it remained free of frozen snow and ice and was comfortable to hold. An example design is shown in 7.21.

This, clearly, could be taken further. There are many variants of each product that was described above – some using other materials, coatings, and processes than those listed here, from which more could be learnt. Even a brief survey such as this is sufficient to demonstrate that the method has potential.

Inline Skates

Roller-skating has existed since the 1880s. Inline skates are much more recent, first commercialized in the 1980s by the Rollerblade company. The first commercially successful Rollerblade skate was an ice hockey boot fitted with polyurethane wheels, a rubber heel brake, and a fiberglass runner. Since then, the skates have evolved and differentiated, some with rugged wheels for “mountain” skating, others with detachable boots allowing quick conversion from shoes to inline wheels, and some with elements that appeal specifically to women or children.

Material Selection – Similarity

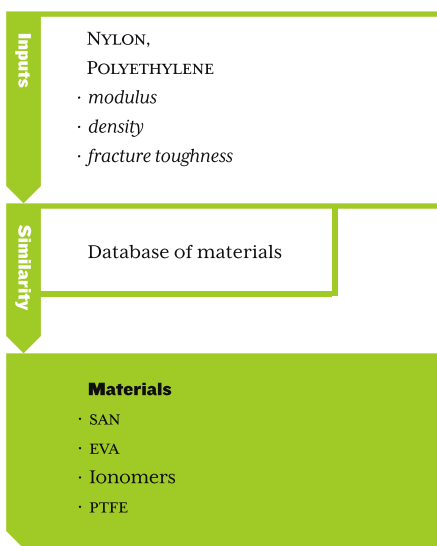
And now the challenge: a request to design an inline skate boot that will be used in training for cross-country skiing. It must be stiff but flexible, lightweight, and impact resistant. Stiffness is needed so that the boot can be attached to the wheel platform and provide adequate rigidity for ankle support; flexibility is required because, when used for cross-country training, the heel will lift off the wheel platform and the boot will flex; and lightness is required to limit the weight that the athlete must carry. Impact resistance is important to cope with collisions with objects or the ground. The designer starts with the pre-conception (drawn from experience with ice hockey boots) that nylon or polyethylene could be possible material solutions. The set of possible material solutions is expanded by a search for materials that match critical attributes of the two materials. Stiffness and impact resistance depend on the material properties modulus and fracture toughness; if, in addition, lightweight is wanted it is the values of these per unit weight that count. Thus, we seek to match modulus/density and fracture toughness/density (7.22).

To match the performance of nylon and polyethylene, it is important that the designer selects materials that span the range of each attribute that has been specified. The boot of an inline skate could be made of a toe and heel (SAN) with flexible connection between (EVA). The boot must now be designed so that it can be attached to the platform at one (toe only) or two points (toe and heel) so that cross-training for cross-country

skiing is possible, but that is a detail of design that is not considered here. The path of material selection for this case study and an example design for an inline skate are shown in Figures 7.23 and 7.24, respectively.

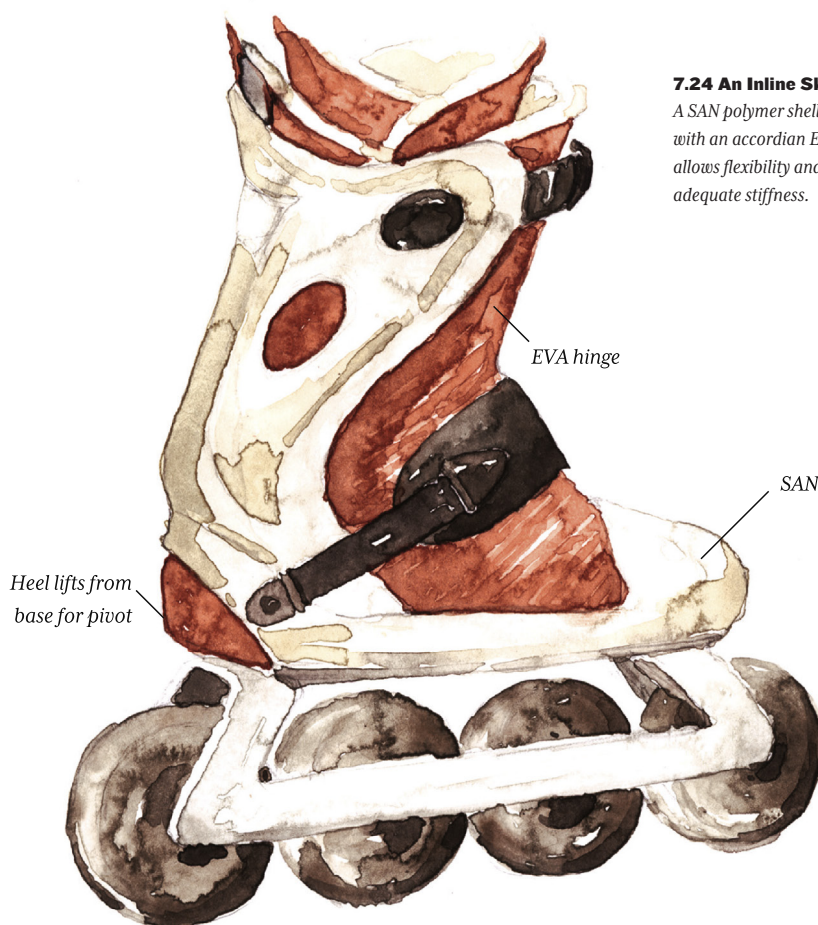
Conclusions

These case studies are brief and the details of each design are not fully resolved; they serve primarily as demonstrations of each of the methods of selection introduced in earlier chapters, and of the way they can be combined to suggest innovative material solutions.



7.23 Selection by Property Matching

The selected materials have modulus/density and toughness/density that match those of (a) nylon and (b) polyethylene.



7.24 An Inline Skate

A SAN polymer shell is integrated with an accordion EVA hinge that allows flexibility and provides adequate stiffness.

Further Reading

Ashby, M.F. (2012) “Materials Selection in Mechanical Design,” 4th edition, Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-4357-9. (A text that complements this book, presenting methods for selecting materials and processes to meet technical design requirements, and presenting a large number of material property charts.)

Ashby, M.F., Shercliff, H.R. and Cebon, D. (2013) “Materials: Science, Engineering, Processing, Design,” 3rd edition, Butterworth-Heinemann, Oxford, UK. ISBN 978-0-7506-8391-3. (An introductory text using a design-led approach to the selection of engineering materials and processes.)

Bailey, K.D. (1995) “Typologies and Taxonomies, an Introduction to Classification Techniques,” Sage Publishers, Thousand Oaks, CA and London, UK. ISBN 0-803-95259-7. (A monograph on classification in the social sciences, with a forceful defense of its applications there and elsewhere.)

Bakewell, K.G.B. (1968) “Classification for Information Retrieval,” Clive Bingley, London, UK. ISBN 85157-014-3. (A collection of six lectures on different types of classification, interesting for the contribution on faceted classification, the precursor of relational database structures.)

Charles, J.A., Crane, F.A.A. and Furness, J.A.G. (1997) “Selection and Use of Engineering Materials,” 3rd edition, Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-3277-1. (A Materials Science approach to the selection of materials – nothing on aesthetics.)

Dieter, G.E. (1991) “Engineering Design, A Materials and Processing Approach,” 2nd edition, McGraw-Hill, New York, NY, USA. ISBN 0-07-100829-2. (A well-balanced and respected text focussing on the place of materials and processing in technical design. Nothing significant on industrial design.)

Everitt, B. (1974) “Cluster Analysis,” Heinemann Educational Books Ltd, London, UK. ISBN 0-435-82298-5. (A comprehensible introduction to cluster analysis.)

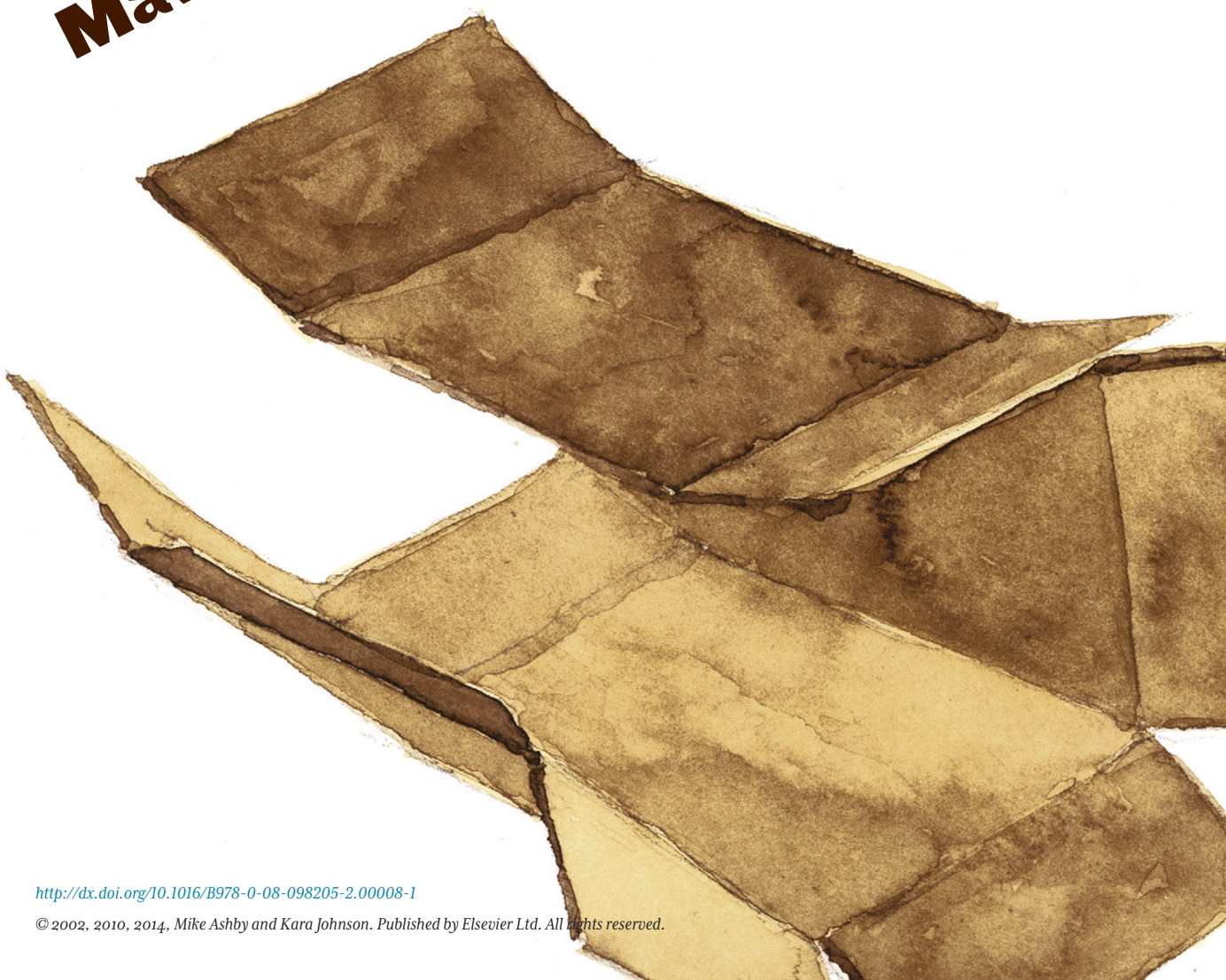
Haberlandt, K. (1997) “Cognitive Psychology,” 2nd edition, Allyn and Bacon, Boston, MA, USA. ISBN 0-205-26416-6. (An introduction to the psychology of choice and decision-making with insights that are useful here.)

Kolodner, J.L. (1993) “Case-Based Reasoning,” Morgan Kaufmann Publishers Inc, San Mateo, CA, USA. ISBN 1-55806-237-2. (Case-based reasoning is a technique for storing information about past situations in ways that allow useful information retrieval to solve present problems; the methods are well-presented in this book.)

Zwicky, F. (1969). “Discovery, Invention, Research”, Macmillan Co. Toronto, Canada. Library of Congress No. 69-10785. (An introduction to the morphological approach to problem solving.)

Chapter 8

Materials and Sustainability

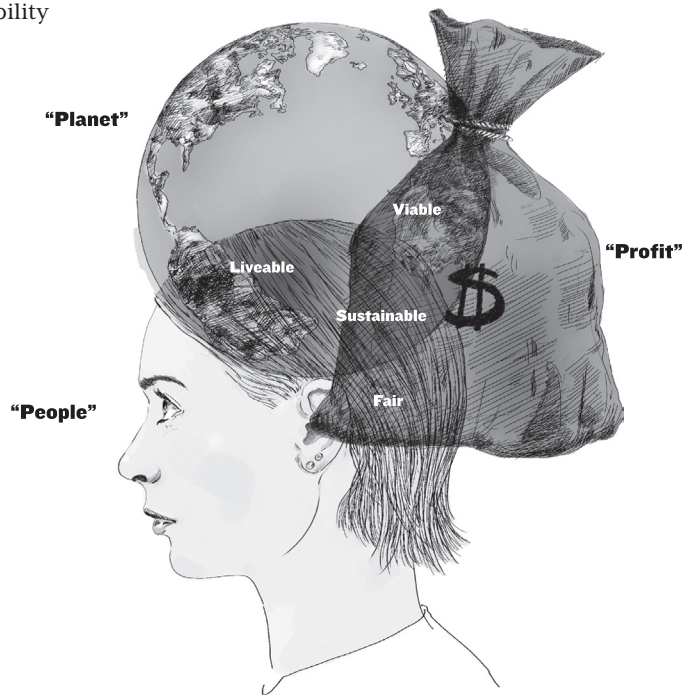


Here is a much-quoted definition of sustainable development: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (The Brundtland Report of the World Council on Economic Development ([WCED, 1987](#))). It sounds right. But how is it to be achieved? And where do materials fit in? The definition gives no concrete guidance.

So let's try another view of sustainability, one expressed in the language of accountancy: the Triple Bottom Line, or 3BL ([8.1](#)). The idea is that a corporation's ultimate success or health should be measured not just by the traditional financial bottom line, but also by its social/ethical and environmental performance. Instead of just reporting the standard bottom line of the income and outgoings (“Profit”) the balance sheet should also include the

bottom lines of two further accounts: one showing the environmental (“Planet”) and one showing the social (“People”) balance. Sustainable business practice requires that the bottom lines of all three columns show positive balances, represented by the “Sustainable” sweetspot on [Figure 8.1](#). This sounds right too, and because it seems like an extension of normal accounting practice, many businesses claim to implement 3BL reporting. But

8.1 Triple Bottom Line (or “PPP” thinking).



how are the environmental and social performances of a business to be measured and aggregated? Is it even possible that all three be positive at the same time? And again: where do materials fit in? The 3BL concept does not give clear guidance.

The Role of Materials

The Three Capitals

We make better progress if we separate the ideas presented in Figure 8.2 and unpack their content, so to speak. Here a view of sustainability seen through the lens of economics can help. Global or national “wealth” can be seen as the sum of three components: the net manufactured capital, the net human capital, and the net natural capital. The sum of all three, the net comprehensive capital, is a measure of national or global wealth (Figure 8.2). They are defined like this:

- Manufactured capital – industrial capacity, institutions, roads, built environment, financial wealth (GDP)
- Human capital – health, education, skills, technical expertise, accumulated knowledge, happiness
- Natural capital – clean atmosphere, fresh water, fertile land, productive oceans, minerals, and fossil energy.
- Comprehensive capital – the sum of all three capital assets.

Each one can (with some difficulty) be quantified in a common measure, \$, say, although doing so with precision has obvious difficulties. But it is possible to assign a sign and order of magnitude to the change in each capital, reporting whether it is positive or negative, large or small. “Strong” sustainability, in

this picture, is development that delivers positive growth in all three capitals. “Weak sustainability” is development that delivers positive comprehensive capital, ensuring that the sum of the capitals passed on to future generations is positive, even if one of them is diminished.

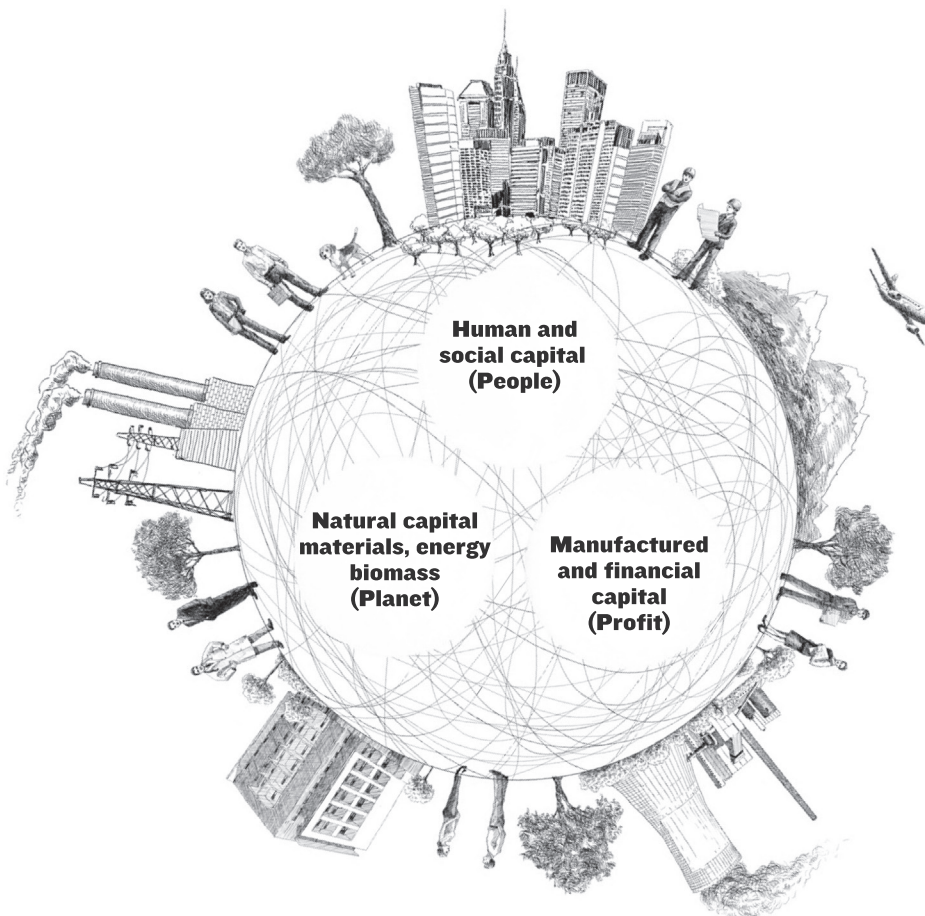
The main force, today, that drives change in the three capitals is the pressure for economic growth. An economy that grows is seen as healthy; one that does not is stagnant, and one that is in recession is sick.

Positive economic growth increases manufactured capital and it is seen as so essential to the welfare of a nation that its influence on the other two capitals is sometimes treated as secondary. Economic growth may contribute to human capital by enabling greater education and health

care, for instance, or it may diminish it by unfair labor practices and social inequity. And unfettered economic growth must, in the long run, diminish natural capital by consuming irreplaceable resources.

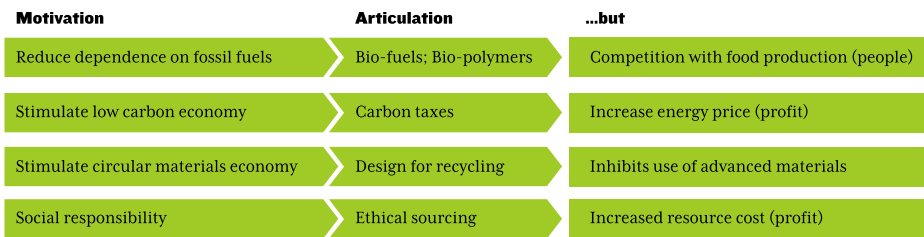
Competing Articulations of Sustainable Technology

Perceptions such as these have stimulated activities to diminish the undesired impacts of economic growth – particularly to diminish resource consumption and emission release. These activities, of which there are many examples, are generally presented as contributions to sustainable development. Following [Mulder et al. \(2011\)](#) we will refer to them as “articulations” of sustainable technology. The difficulty with almost all of



8.2 The Three Capitals (and their sum).

8.3 Conflicts in Sustainability
Competing articulations of sustainable technology conflict



them is that they conflict: an articulation that addresses one aspect of the problem may create another (8.3 gives examples). Advocates of bio-fuels and bio-polymers do so because they diminish dependence on fossil hydrocarbons, but the land required to grow them is no longer available for the cultivation of food. Carbon taxes are designed to stimulate a low-carbon economy, but they increase the price of energy, and hence of materials and products. Design for recycling is intended to meet the demand for materials with less drain on non-renewable resources, but it constrains the use of light-weight composites, which can enable fuel-saving in vehicles, because these composites cannot be recycled. The motivation for ethical sourcing of raw materials is that of social responsibility but the side-effect is to increase the prices paid for resources.

Thus sustainable development is not one thing, it is many. Figure 8.4 is an attempt to illustrate this. Here the three “P” circles of the triple bottom line have been separated and given their fuller titles. They now sit on the edge of a pond in which swim some of the many articulations of sustainable development. The arrows suggest their interactions, green when positive, red when damaging. Arguments can be made for the merits of any one of them if the interactions

are ignored, but the picture becomes much more complex as soon as they are switched on to give a closer approximation to reality. It is not helpful to solve one facet of the sustainability problem if the solution aggravates or creates others. Loosing sight of the big picture limits vision and leads to mistaken perceptions and, worse, mistaken legislation. If the figure does nothing else, it brings out the need for a broad view and an even-handed approach if sustainable development is to be tackled in a constructive way.

Meta-Messages: The Bigger Picture

The articulations pictured in Figure 8.4 have certain features in common. Many of them concern the more efficient use of resources. On the technical side, the three P’s are dependent on three efficiencies – three E’s, if you like – energy, bio, and material efficiency. Here we use “efficiency” to mean “service-provision per unit of resource,” with “resource” read as “energy, bio-mass or material.”

Energy efficiency is already widely practiced – the direct cost of energy in energy-using processes is large enough to make it a priority. Bio-efficiency in the form of agronomy, too, is widely practiced – the importance of food-production in the economy makes this also a priority – though bio-efficiency

must include the efficient use of more than just bio-mass. Material efficiency, by contrast, is not treated with the same imperative, as the waste stream created by developed economies demonstrates.

Why? Commodity prices, corrected for inflation, have declined over time for many decades, but have risen steeply in the recent past. The cost of energy, too, was nearly steady over many decades; but has surged upwards in the recent past. Global GDP, over this same period, has increased steadily and with it, of course, the cost of labor. So, for decades, the ratio of material cost to labor cost declined (the same was true of energy). It became increasingly attractive to design to minimize the use of labor, even if that meant being extravagant with materials. Repair and maintenance require labor, making it cheaper to discard products than to fix or upgrade

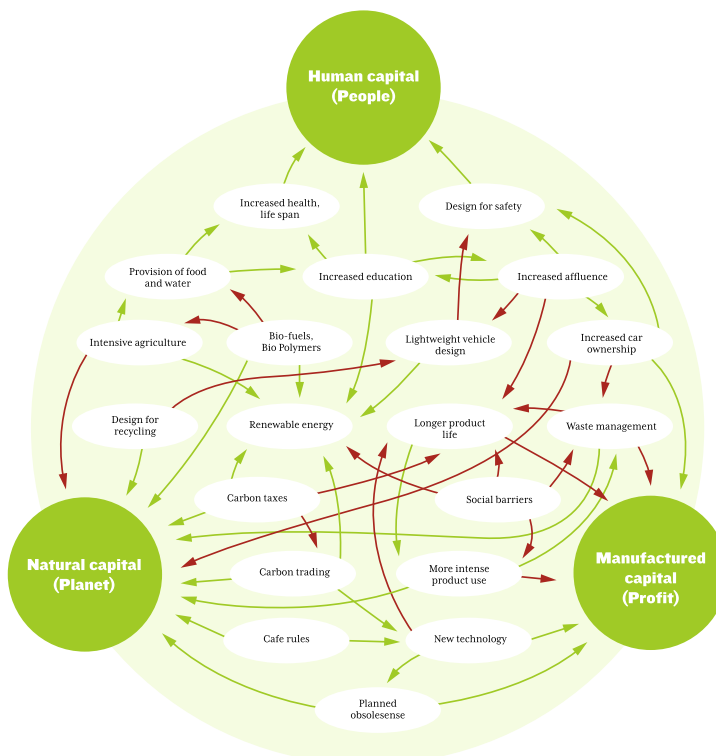
them. Virgin materials became so cheap that there was little financial incentive to recycle them.

This is now changing. The recent spikes in materials prices and the accompanying spikes in the price of energy begin to shift priorities toward greater material efficiency.

Material Efficiency

Nature uses materials efficiently. The tallest tree captures the most sunlight. The strongest predator captures the most prey. Plants and animals compete for these and other resources. Those that use these resources most efficiently are the ones that survive. Nature sets examples of material efficiency by favoring evolution that minimizes the resources consumed per unit of function.

In human terms, material efficiency means providing more material services



8.4 Sustainable Development

Some of the many articulations of sustainable development and their interactions.

with less material production. Remember that material production is not the same as material consumption. Material production measures the quantity of materials created per year from ores, feedstock, and energy, and thus draws on natural resources. Material consumption measures the quantity of materials used in manufacture of all types per year. Consumption is greater than production because of the contributions of material recycling and reuse. The aim of increased material efficiency is to accommodate the material consumption required for necessary goods and services while producing as little material as possible.

Most mineral resources are sufficient to meet current demand, but as grades dwindle, it takes more energy to mine and refine them. Thus constraints on material supply may arise because of unmanageable energy requirements or because the environmental consequences of extraction and processing become unacceptable. And there is the geo-political dimension: mineral scarcity conditions for politically-motivated barriers to free trade, constraining material supply.

There are, then, at least four compelling motives for increasing material efficiency:

- To minimize the depletion of non-renewable material resources
- To reduce the dependence of developed countries on imports, particularly of materials already in short supply;

- To reduce the demand on other resources, particularly energy; and
- To reduce unwanted emissions generated by material production and use.

Four broad strategies are available for increasing material efficiency (8.5):

- Improved material technologies
- Material-efficient engineering design
- The use of economic instruments
- Social adaptation (change of lifestyle)

The first of these – material technology, shown as the upper-left block of [Figure 8.5](#) – seeks ways to produce materials more efficiently, to improve their properties, to increase their functionality, and to develop new, cost-effective ways of reusing them. The second – engineering design (upper-right) – deploys the methods of engineering design to closing the materials loop to retain materials in use in existing, modified, or new products. These two measures require little change in consumer behavior beyond a willingness to retain and recycle, and an acceptance of recycled and reconditioned materials and products as desirable. The two blocks are labeled “Engineering solutions” on [Figure 8.5](#).

The lower part of the figure introduces strategies of a different sort. The lower-left block – economic instruments – lists some of the ways in which legislation can influence material use and reuse. That at the lower right – social

8.5 Material Efficiency



adaptation – requires a changed view of possession, acknowledging that sole ownership carries responsibilities of product stewardship, accepting shared ownership and use of products, or abandoning ownership entirely and relying instead on service providers.

The quantities of material now in service are very large – large enough to provide all the material services of modern life. If these materials can be kept in service by prolonging product life, by reusing products or their components, or by recycling the materials they are made of to make new products, the need for material production would almost vanish. That, of course, is a utopian view, but the benefits of retaining material in service rather than discarding them remain large. The idea is summarized in the words: reduce, reuse, recycle.

Consumption and Waste

When stuff is useful, we show it respect

and call it “material”. When the same stuff ceases to be useful we cease to respect it and call it “waste.” Is waste inevitable? The short answer is yes – it is a consequence of one of the inescapable laws of physics: that entropy can only increase. A fuller answer is yes, but. The “but” has a number of aspects. That is what this section is about.

First, a calibration. We (the global we) are consuming materials at an ever faster rate. The first owner of a product, at end of life, rejects it as “waste.” So waste, too, is generated at an ever growing rate. We can’t go on doing this for ever. Where is all this waste going to go? Waste disposal is already a problem in Europe, Japan, and the US, and will become so elsewhere. We have to move toward a circular materials economy, meaning one in which materials are not just used once and the discarded, but instead are fed back into the economy by recycling or reusing them.

The Role of Design

What have you discarded lately that still worked or, if it didn't, could have been fixed? Changing trends, urged on by seductive advertising, reinforce the desire for the new and urge the replacement of still-useful objects. Industrial design carries a heavy responsibility here – it has, at certain periods, been directed toward creative obsolescence: designing products that are desirable only if new, and urging the consumer to buy the latest models, using marketing techniques that imply that acquiring them is a social and psychological necessity.

But that is only half the picture. A well-designed product can acquire a value with age, and – far from becoming unwanted – can outlive its design life many times over.¹ The auction houses and antique dealers of New York, London, and Paris thrive on the sale of products that, often, were designed for practical purposes but are now valued more highly for their aesthetics, associations, and perceived qualities. People do not throw away products for which they feel emotional attachment. So there you have it: industrial design both as villain and as hero. Where can it provide a lead?

When your house no longer suits you, you have two choices: you can buy a new house or you can adapt the one you have got, and in adapting it you make it more personally yours. Houses allow this. Most other products do not; and an old product (unlike an old house) is often perceived to be incapable of change and to have such low value that it is simply

discarded. That highlights a design challenge: to create products that can be adapted and personalized so that they acquire, like a house, a character of their own and transmit the message “keep me, I'm part of your life.” This suggests a union of technical and industrial design to create products that can accommodate evolving technology, but at the same time are made with a quality of material, design, and adaptability that creates lasting and individual character, something to pass on to your children.

To get further we need to ask: why do we throw things away?

Why Do We Throw Things Away?

The rapid turnover of products we see today is a comparatively recent phenomenon. In earlier times, furniture was bought with the idea that it would fill the needs not just of one generation but of several – treatment that, today, is reserved for works of art. A wrist watch or a gold pen were things you used for a lifetime and then passed on to your children. No more. Behind all this is the question of whether the value of a product increases or decreases with age.

A product reaches the end of its life when it's no longer valued. The reason, frequently, is not the obvious one that the product just stopped working. The life expectancy² is the least of:

- The physical life, meaning the time in which the product breaks down beyond economic repair;
- The functional life, meaning the time when the need for it ceases to exist;

1. For an organization with such an ideal...www.ewerally-yours.nl.

2. This list is a slightly extended version of one presented by Woodward D.G. (1997) “Life-cycle costing”, *Int.J. Project Management*, vol. 15, pp 335 - 344.

- The technical life, meaning the time at which advances in technology have made the product unacceptably obsolete;
- The economical life, meaning the time at which advances in design and technology offer the same functionality at significantly lower operating cost;
- The legal life – the time at which new standards, directives, legislation, or restrictions make the use of the product illegal
- And finally the loss of desirability – the time at which changes in taste, fashion, or aesthetic preference render the product unattractive.

One obvious way to reduce resource consumption is to extend product life, making it more durable. But product life has more than one meaning: we've just listed six. If you wish to design to extend product life you must cover all of them. Accept, for the moment, that a product has reached to the end of its life. What are the options? [Figure 8.6](#) introduces the options: landfill, combustion for heat recovery, recycling, re-engineering, and reuse.

Landfill and Combustion

Much of what we now reject is committed to landfill. Already there is a problem – the land available to “fill” in this way is already, in many countries, almost full. Administrations react by charging a landfill tax, currently somewhere near

\$50 per tonne and rising, seeking to divert the waste into other channels.

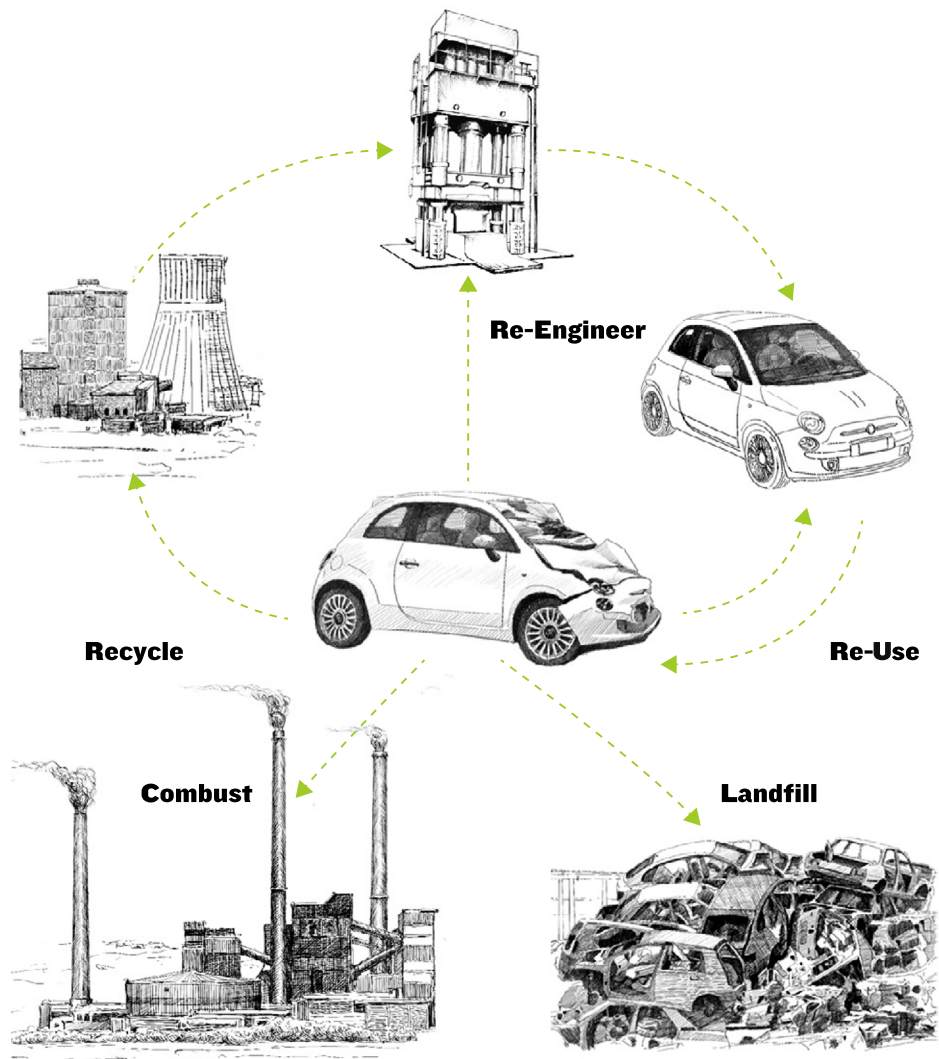
Materials, we know, contain energy. Rather than throwing them away it would seem better to retrieve and reuse some of their energy by controlled combustion, capturing the heat. But this is not as easy as it sounds. First there is the need for a primary sorting to separate combustibles from non-combustible material. Then the combustion must be carried out under conditions that do not generate toxic fumes or residues, requiring high temperatures, sophisticated control, and expensive equipment. The energy recovery is imperfect partly because it is incomplete and partly because the incoming waste carries a moisture content that has to be boiled off. Thus useful energy can be recovered by the combustion of waste, but the efficiency is low, the economics unattractive and the neighbors can be difficult.

Re-Engineering and Life Extension

Re-engineering is the repairing or upgrading of the product or of its recoverable components. Certain criteria must be met to make it practical. One is that the design of the product is fixed – as it is with aircraft once an airworthiness certificate is issued – or that the technology on which it is based is evolving so slowly that there remains a market for the restored product. Here are some examples: car tires and engines, road and rail infrastructure; office space and office equipment, particularly printing equipment, copying machines, and communication systems. These are services; the product providing them is unimportant

8.6 End-of-Life

End-of-life options building on the material lifecycle presented in Figure 2.3.



3. What most of us see as waste can become the material of invention to the artist. For remarkable examples of this, visit the Musée International des Arts Modestes, 23 quai du Maréchal de Lattre de Tassigny, 34200 Sète, France (www.miam.org).

4. A sign above a store in an English town: "We buy junk. We sell antiques".

to those who need the service so long as it works well. It makes more sense to lease a service (as we all do with telephone lines, mobile phone, and Internet service provision and much else) because it is in the leasers' interests to maximize the life of the equipment providing it.

Re-Use and Recycling

Re-Use is the redistribution of the product to a consumer sector that is willing to accept it in its used state, perhaps to reuse for its original purpose (a sec-

ond hand car, for instance), perhaps to adapt to another (converting the car to a hotrod or a bus into a mobile home).³ The challenge is to link buyers to sellers – a question of communication. House listings, and used car and boat magazines exist precisely to provide channels of communication. Charity shops pass on clothing, objects and junk,⁴ acquired from those for whom they had become waste, and sell them on to others who perceive them to have value. And here's a thought: the most effective tool ever

devised to promote reuse is probably e-bay, successful because it provides a global channel of communication.

Waste is only waste if nothing can be done to make it useful. It can also be a resource. Recycling is the reprocessing of recovered materials at the end of product life, returning them into the use-stream. It is the most effective way to extract value from the waste-stream.

Recycling requires energy, and this energy carries its burden of gases. But the recycle energy is generally small compared to the initial embodied energy, making recycling – when it is possible at all – an energy-efficient proposition. It may not, however, be one that is cost-efficient; that depends on the degree to which the material has become dispersed. In-house scrap, generated at the point of production or manufacture, is localized and is already recycled efficiently (near 100% recovery). Widely distributed “scrap” – material contained in discarded products – is much more expensive to collect, separate and clean. Many materials cannot be recycled, although they may still be reused in a lower-grade activity; continuous-fiber composites, for instance, cannot be re-separated economically into fiber and polymer in order to reuse them, though they can be chopped and used as fillers. Most other materials require an input of virgin material to avoid build-up of uncontrollable impurities. Thus the fraction of a material production that can ultimately re-enter the cycle of [Figure 8.6](#) depends both on the material itself and on the product into which has been incorporated.

The recycling of metals is highly developed. Metals differ greatly in their density, in their magnetic and electrical properties, and even in their color, making separation comparatively easy. The value of metals, per kilogram, is greater than that of other materials. All these help to make metal recycling economically attractive. There are many limitations on how recycled metals are used, but there are enough good uses that the contribution of recycling to today’s consumption is large.

The same cannot be said of polymers. Commodity polymers are used in large quantities, many in products with short lives, and they present major problems in waste management, all of which, you would think, would encourage effective recycling. But polymers all have nearly the same density, have no significant magnetic or electrical signature, and can take on any color that the manufacturer likes to give them. They can be identified by X-ray fluorescence or infrared spectroscopy, but these are not infallible and they are expensive. Add to this that many are blends or contain fillers or fibers.

Add further that the recycling process itself involves a large number of energy consuming steps. Unavoidable contamination can prevent the use of recycled polymers in the product from which they were derived, restricting them to more limited use. For this reason the value or recycled polymers – the price of which they can be sold – is about 60% of that of virgin material.

A consequence of this is that the recycling of many commodity polymers is low. Increasing the recycle fraction

8.7 Recycling Marks

Top: recycle marks for commodity polymers. Bottom: more explicit marks that detail blends, fillers and reinforcements. The frits is polypropylene with 20% talk filler. The second is polycarbonate-ABS blend reinforced with glass fibers.





8.8 Design with Recycled

Materials (a) Quilt, spinsagoodya.rn.com, (b) supermarket chair, reestore.com, (c) container homes from weburbanist.com, (d) mobile home, bus, transitionbus.org and www.miam.org.

is a question of identification, and here there is progress. In Figure 8.7 the standard recycle marks are ineffective because they do not tell the whole story. The two at the bottom show an emerging identification system. Here polymer, filler, and weight fractions are all identified. The string, built up from the abbreviations listed in the Appendix to this chapter, gives enough information for effective recycling.

Designing with Recycled Materials

What most of us see as waste can become the materials of invention to the innovative designer. Here are some examples.

Quilting is the art of creating color palettes and patterns, even stories, from left-over or scrap segments of materials. The chair transforms a familiar (and often disparaged) object into something reminiscent of Marcel Breuer's minimalist tubular steel designs of the 1920s.

The modular housing adapts redundant shipping containers to create modernistic, expandable living space. The mobile home is a re-furnished school bus.

These are one-offs. They are imaginative, delightful, even inspirational. But they do little to solve the problem of waste. That needs designs that use recycled materials on an industrial scale. For this, a large, stable supply of recycled material of consistent quality is essential. This, in turn, is dependent on a profitable recycling infrastructure, or, if not profitable, one that is appropriately subsidized.

Given all that, what are the advantages of recycling? Proponents point out that recycling reduces consumption

of primary (virgin) raw materials, saves energy, and reduces emissions. It reduces the need for investment in incineration plant and landfill sites. And it creates jobs. Critics of recycling dispute these claims, arguing that the energy used in collection, transport, and reprocessing outweighs the gains, and that the low-quality jobs created by recycling are poor compensation for the more skilled employment in mining and forestry that they displace. One fact, however, remains: for a sustainable, more equitable future with a growing global population we must manage with less material per person per year than we do now. Recycling is a flexible, manageable way to contribute to this goal.

There is "Design for..." and there is "Design with...." Start with the first. The biggest obstacle to recycling is probably that most products are not designed for recycling at end of life. No great surprise -the creator of competitive products, in the past, had more pressing priorities. But that has now changed. Governments now legislate mandatory targets for recycling, particularly for vehicles and for electronics. And they can (and do) use their purchasing power to create markets for products containing recycled materials. For all these reasons, design for recycling is now an essential part of the design process.

Design with recycled materials means recognizing their weaknesses and designing around them. Recycled metals may contain impurities not found in virgin stock, and the impurities may vary from batch to batch. They create potential problems in meeting the

rigorous materials specs of the medical and food-processing sectors and could compromise compliance with legislation such as REACH and COSHH.⁵ There are some simple guidelines for designing with recycled plastics. Specify thicker walls or features that enhance rigidity in a design where increased strength must compensate for reduced strength in material. Select applications where color is not critical – additional colorants can be added to mask the original color of the material. Use materials that are easy to recycle. Minimize the number of different polymers in a product – separating them at end of life is difficult. Select materials that are in mutually compatible groups, e.g. polyolefins (PE, PP). PET, PVC, HDPE, and ABS are easier to recycle than most other polymers. To aid recycling, avoid materials which are difficult to separate such as laminates, fire retardants, and fiberglass reinforcements. Avoid polluting elements such as stickers that interfere with recycling, or glues.

Recycled polymers pick up rogue content of other polymers, changing their ability to be molded. The precise composition control possible with virgin glass (controlling optical and processing properties) is lost with recycled glass.

This sounds a bit discouraging. But many applications remain in which recycled materials perform well, and in doing so reduce cost, reduce landfill, and reduce demand on natural resources.

Figure 8.9 two examples.

Paper and cardboard make up to 50% of household waste. Paper carrier bags are used in vast quantities, often only

once. They are examples of paper-based products that can be made from recycled paper with no loss of functionality. Recycled paper is not necessarily cheaper than that made directly from trees, but increasing its use reduces the volume of material going to landfill.

The EPA buildings in Arlington, VA, make extensive use of recovered materials in their construction. The concrete contains recycled concrete and blast furnace slag as aggregate, bonded with cement with high fly-ash content. Fly-ash is used in bonded stone for the facing. Ceiling tiles and wall-board contain gypsum from power-station flue gas. Wood flooring is based on salvaged lumber. Carpet tiles are backed with used tires and recycled carpet. Scrap tires provide subsoil drainage. These are now established building practice, possible with any new-build.

The Problem of Packaging

Few applications of materials attract as much criticism as their use in packaging. Packaging ends its functional life as soon as the package is opened. It is ephemeral, it is trite, it generates mountains of waste and most of the time it is unnecessary.

Or is it? Think for a moment about the most highly developed form that packaging takes: the way we package ourselves. Clothes provide protection from heat and cold, from sun and rain. Clothes convey information about gender, and ethnic and religious background. Uniforms identify membership and status, most obviously in the military and the church, but also in other hierarchical organizations: airlines, hotels, department stores, and even utility

5. *The Registration, Evaluation, Authorization and Restriction of Chemical Substances (REACH) Directive and Control of Substances Hazardous to Health (COSHH) Directive of the European Union.*

(a)



(b)



8.9 Paper & Concrete

(a) Paper bag, mojopromotions.co.uk, (b) recycled concrete in EPA building, epa.gov/industrialmaterials, (image courtesy of civiz.com)

8.10: Bio-polymer nomenclature.

Nomenclature: Bio-polymers	
Polylactic acid	PLA
Polyhydroxyalkanoates	PHA
Cellulose polymers	CA, CAP, CAB
Thermoplastic starch	TPS
Polycaprolactone	PCL
Nomenclature: Oil-based polymers	
Polypropylene	PP
High density polyethylene	PE-HD
Low density polyethylene	PE-LD
Acrylonitrile-butadiene styrene	ABS
Polystyrene	PS
Nylon 66	PA
Polyethylene terephthalate	PE

6. See, for instance, The Packaging Federation, www.packagingfedn.co.uk, or the Flexible Packaging Association, www.flexpack.org.

companies. And at a personal level clothes do much more: they are an essential part of the way we present ourselves. And while some people make the same clothes last for years, others wear them only once or twice before – for them – they become “waste” and are given to a charity shop.

Fine, you may say, we need packaging of that sort; but products are inanimate. What’s the point of packaging for them? The brief answer: products are packaged for precisely the same reasons that we need clothes: protection, information, affiliation, status, and presentation.

So let us start with some facts. Packaging makes up about 18% of household waste, but only 3% of land-fill. Its carbon footprint is 0.2% of the global total. Roughly 60% of packaging in Europe, rather less in the US, is recovered and used for energy recovery

or recycling. Packaging makes possible the lifestyle we now enjoy. Without it, supermarkets would not exist. By protecting foodstuffs and controlling the atmosphere that surrounds them packaging extends product life, allows access to fresh products all year round, and reduces food waste in the supply chain to about 3%; without packaging the waste is far higher. Tamper-proof packaging protects the consumer. Pack information identifies the product, its sell-by date (if it has one) and gives instructions for use. Brands are defined by their packaging – the Coca-Cola bottle, the Heinz soup can, Kellogg products – essential for product presentation and recognition.

The packaging industry⁶ is well aware of the negative image that packaging, because of its visibility, holds, and it strives to minimize its weight and volume. There are of course exceptions but there has been progress in optimizing it – providing all its functionalities with the minimum use of materials. The most-used of these – paper, cardboard, glass, aluminum, and steel – have established recycling markets (see below). Much packaging ends up in household waste, the most difficult to sort. The answer is better waste-stream management in which the sorting is done by the consumer via marked containers. The protective function of much packaging requires material multi-layers that cannot be recycled but which, if sorted, is still a source of energy.

So, the bottom line. Legislating packaging out of existence would require major adjustment of lifestyle, greatly increase the waste stream, deprive

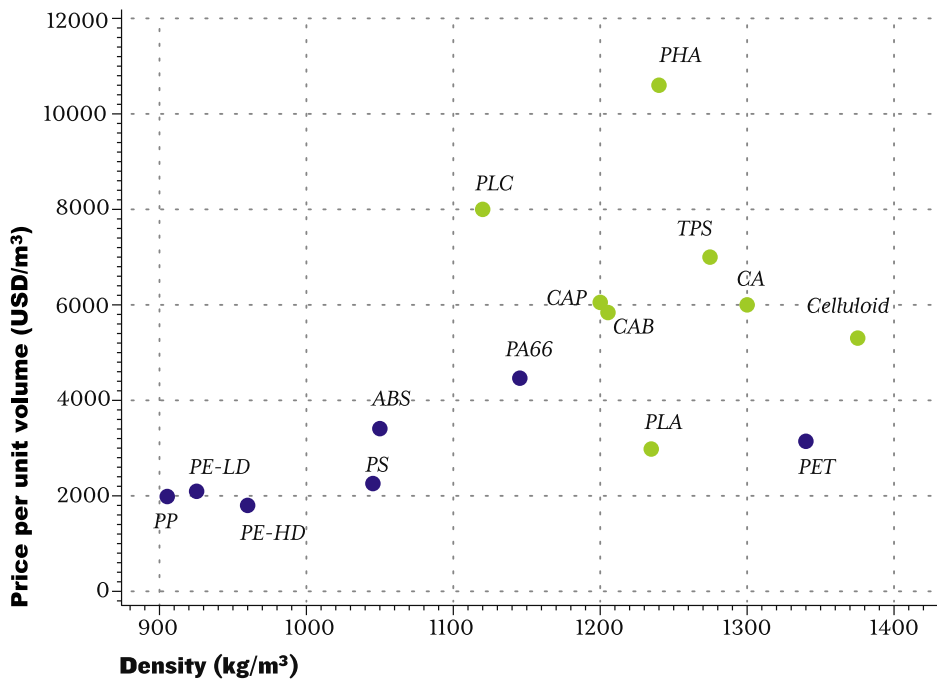
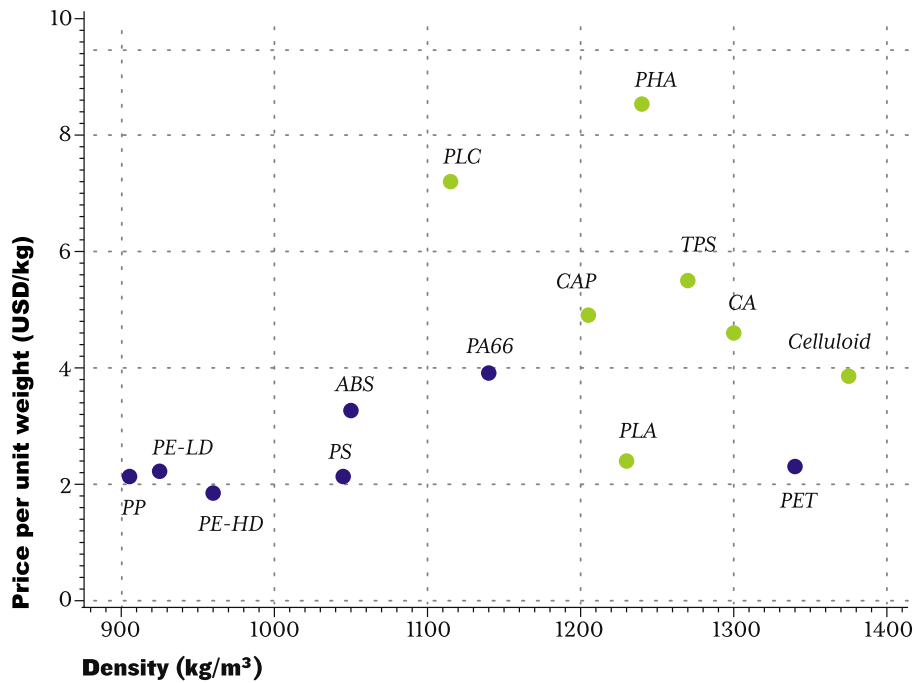
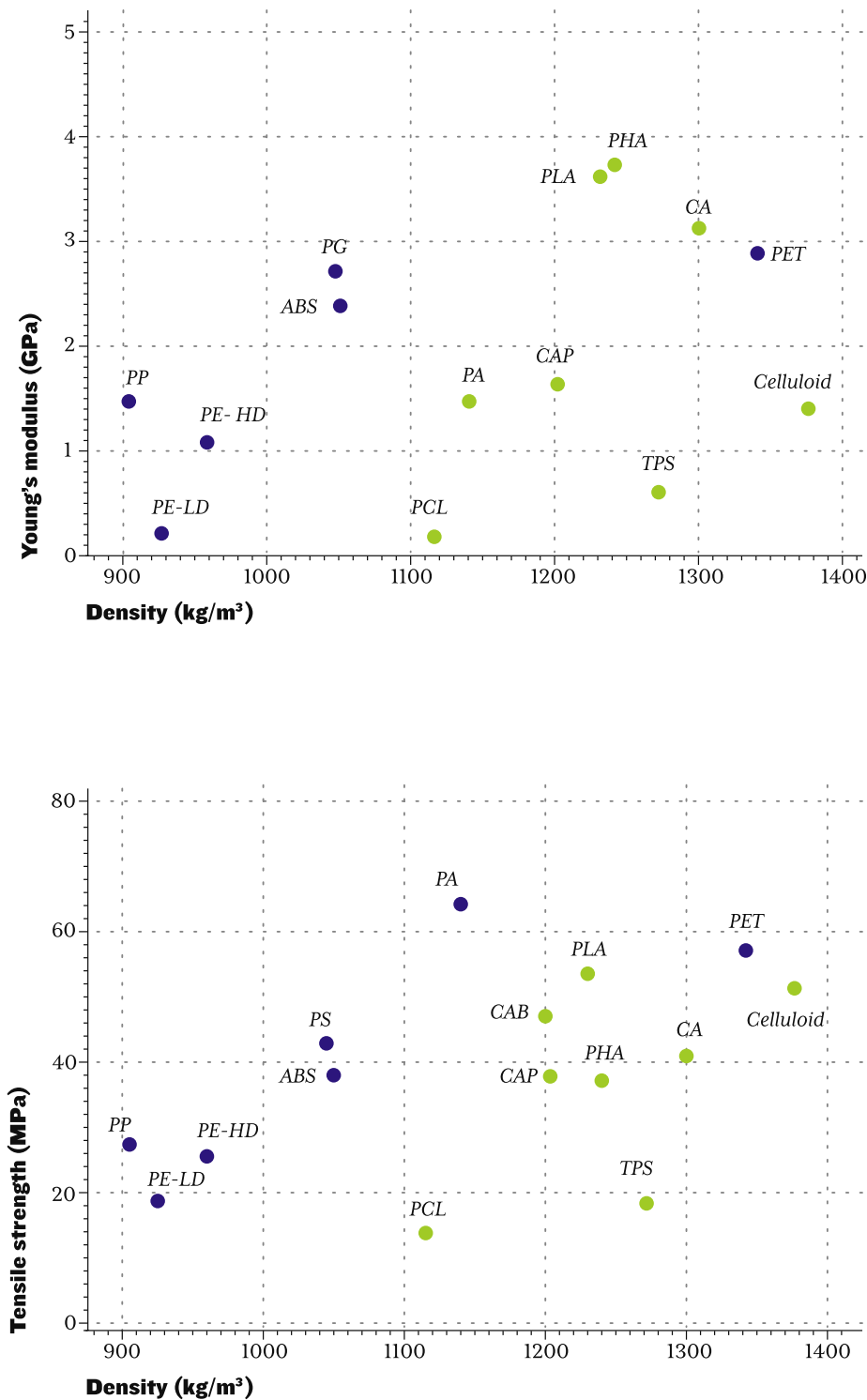


Figure 8.12
Young's modulus, tensile strength,
and density of commodity oil base
polymers (blue) and bio-polymers



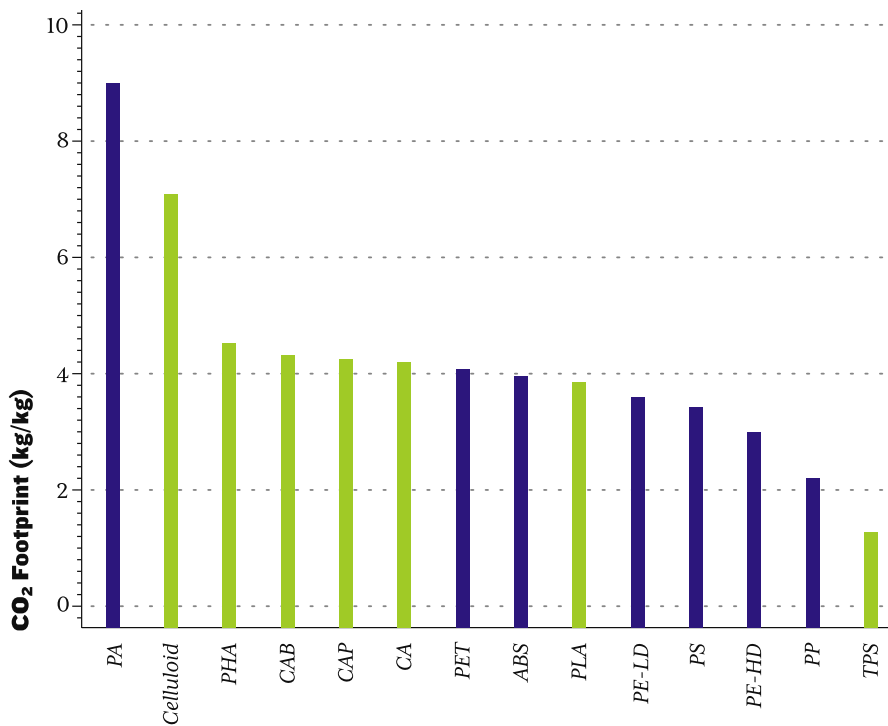
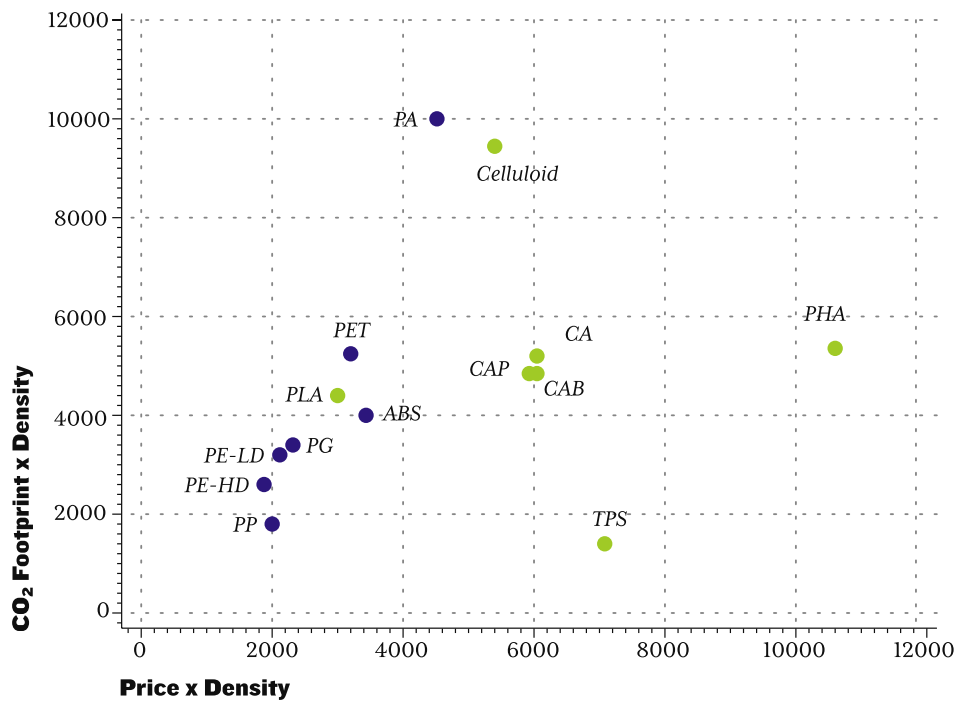


Figure 8.13

The carbon footprint and price of commodity oil base polymers (blue) and bio-polymers (green).



consumers of convenience, product protection, and hygienic handling. The challenge is that of returning as much of it as possible into the materials economy.

Bio-polymers

Nature does wonderful things with bio-polymers, some as simple as starch, others as complex as DNA. Could we not do the same? Well, in one way we do: think of the ways that wood, cork, rubber, leather, skin, cotton, wool, or silk are used in product design. But these are vicarious uses of materials that nature synthesized for a different purpose. Could we not synthesize our own bio-polymers? Why is this interesting? Conventional commodity polymers (plastics) are derived from oil. This is quite a good way to use oil, certainly better than just burning it. But the resistance of plastics to degradation causes a waste problem, and their synthesis from oil gives them a large carbon footprint and a vulnerability to the wild fluctuations of oil price. Synthetic bio-polymers appear to offer an escape from these problems, giving them greener credentials than the oil-based plastics they replace.

This perception has driven the expansion of bio-polymer production (roughly half a million tonnes in 2012), most of it used in packaging. The market for bio-polymers is predicted to grow at 22% per year for the next 5 years, despite their high price and lack of a composting infrastructure. So it is worth taking them seriously.

Manufacturing

Most bio-polymers are synthesized from crops such as sugar beet, potatoes, or wheat. In each case the crop is treated, often by fermentation, to extract the monomer. The monomer is then polymerized to make the plastic. The upstream part of these processes tends to be slow and requires heat. The downstream part (polymerization) resembles that for making oil-based polymers.

Properties of Bio-polymers

Bio-polymers have higher densities, and (today) a higher price than commodity oil-based polymers like polyethylene and polypropylene. [Figure 8.11](#) plots the price per kg against density and the price per unit volume (per m³) against density. In a straight substitution of a bio-polymer for a conventional polymer, it is the price per unit volume that is significant. PLA is about 25% more expensive per unit volume than PP, PE, or PS. All the other bio-polymers are much more expensive than this. [Figure 8.12](#) shows two mechanical properties: Young's modulus and Tensile Strength. Those of bio-polymers are broadly comparable with the same two properties of conventional plastics. [Figure 8.13](#) compares the carbon footprints of bio-polymers with those of conventional polymers. With the exception of PLA, bio-polymers are more energy and carbon intensive than commodity polymers. The right-hand plot presents a pessimistic picture. The sweet spot here is at the bottom left (low cost per unit volume, low carbon footprint per unit volume (see [8.12](#))).

Bio-polymers and the Environment

Bio-polymers are widely assumed to have a better eco-character than conventional, oil-derived, polymers, but evidence does not entirely bear this out. [Figure 8.3](#) shows a comparison of the non-renewable energy and the carbon emission per kg associated with making bio- and conventional polymers. Even though the feedstock for the two types is different, the fermentation process used to prepare bio-resins requires heat and thus carries an energy and carbon burden, and the subsequent polymerization step for both types makes almost identical contributions. Bio-polymer production is, of course, in its infancy; as production is scaled up and processing is refined it is expected that bio-polymers will show an environmental gain (see [8.13](#)).

Energy and carbon are not the only issues. The land area required to synthesize conventional polymers is negligible; that for bio-polymers is large, up to 5 m²/kg per year. At that level the production of 1 million tons of bio-polymer per year requires 5000 square kilometers of fertile land. This competition with agriculture is seen by many as the great weakness of bio-polymers; in a world in which one seventh of the population is undernourished, displacing food production to make plastics seem wrong. There is, however, a potential solution to this problem: the use of algae as feedstock. Marine algae require only seawater, sunlight, carbon dioxide, and nutrients to flourish, leaving fresh water and land for food production. Algae multiply fast, producing up to 15 times more feedstock per unit area than land

biomass. Fermenting them to make ethanol and other alcohols allows their synthesis to (bio)polyethylene, (bio)PVC, and (bio)EVA (see [8.14](#)).

And there is the attraction that some bio-polymers are biodegradable: they are broken down into CO₂ and water by microorganisms. A distinction is drawn between biodegradability and compostability, a purely practical term applied to biodegradable packaging that is sufficiently thin that it breaks down by 90% in six months in a standard composter (such packaging is marked with a “Compostable” symbol).

Applications of Bio-polymers

The biggest industrial application of synthetic bio-polymers is the packaging industry, attractive to them because the materials are biodegradable. The medical use of bio-polymers for drug delivery, sutures and prosthetics has a similar rationale: biodegradation makes them disappear when they are no longer needed. The automobile industry experiments with their use for interior panels and trim for a different reason: that it is a step toward making cars more environmentally friendly (though it is not entirely clear that it really does – see below). The problem, today, is their price.

Bio-composites

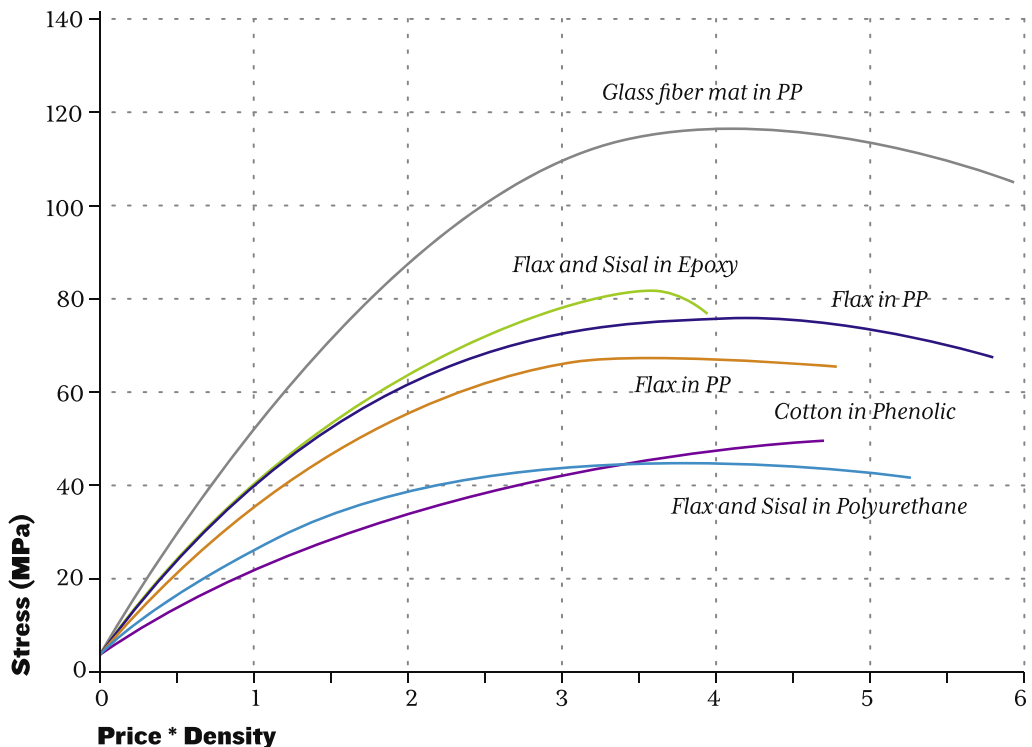
There was a time when cars, like carriages, were largely made of natural materials – wood, fabric, natural rubber; only the engine and drive-train were metal. By the 1970s man-made materials had replaced all of them. Today, however,

natural materials are regaining ground, driven by the environmental agenda. Thus far their application has been limited to trim (flax-fiber reinforced epoxy or furan for interior door panels, for example), for sound insulation (recycled cotton fibers) and seat cushions (coconut fibers in latex), but interest in using plant fibers as reinforcement is growing. The fibers of most interest – flax, sisal, jute, hemp, kenaf, and coir – are annual crops that grow quickly; single fibers have tensile strengths in the range 400–700 MPa. Most current composites (Figure 8.14) use these as reinforcement in thermosetting phenolic or epoxy resins because their fluidity allows them to permeate the fiber array. Almost all bio-composites today use oil-based polymer matrices.

The concept of replacing oil, gas, and coal-based materials by those of similar performance derived directly or indirectly from nature on a significant (and thus large) scale is an appealing one. There are the immediate problems that have been mentioned already: price – bio-polymers and bio-composites with competitive property profiles are not cheap; variability – the properties of bio-materials depend on geography and fluctuations of weather; and the uncertainty of supply, which fluctuates with annual weather patterns.

There are probably ways of solving these problems, but they are not the ultimate difficulty. It is on a different scale. The world has now consumed itself into a corner in which there is not enough productive land to grow both the food we need and at the same time grow

Figure 8.14
Stress-strain curves for natural fiber-reinforced composites compared with that for a glass-polypropylene composite.



structural biomaterials or bio-fuels on a really large scale. Many studies conclude that the population-carrying capacity of the planet is close to saturation. Space, water, and fertile land are the essentials for human habitation and activity. Large-scale replacement of man-made materials by those of nature no longer appears possible.

Figure 8.4 compares five natural fiber-reinforced polymers with glass-fiber reinforced PP. The bio-composites are less stiff (the initial slope of the stress-strain curve), less strong by roughly a factor of 2 and have lower elongation to failure. Nonetheless, the properties are adequate for non-load-bearing interior components and trim in cars. Epoxy or phenolic matrix bio-composites can't be recycled because the binder is a thermoset. This has shifted attention to plant fiber-reinforced thermoplastics, particularly polypropylene, produced in sheet form that can be compression-molded to shape. The obstacles remain the cost, the variability of fiber quality, and the limit on processing temperature (<220 C) required to avoid fiber damage.

Conclusions

Making and using materials inefficiently depletes resources, generates emissions, and creates an uncomfortable dependence on imports. How much can we increase material efficiency before

an enforced reduction in demand for services is the only option left? There are many ways to do so, summarized here. Some come within the remit of the Materials Scientist and Engineer; others involve government incentives and controls, or require changed social perception and behavior.

The greater the number of us that consume and the greater the rate at which we do so, the greater is the volume of materials that our industrial system ingests and then ejects as waste. Real waste is a problem – a loss of resources that cannot be replaced, and there has to be somewhere to put it and that, too, is a diminishing resource.

But waste can be seen differently: as a resource. It contains energy and it contains materials, and – since most product still work when they reach the end of their first life – it contains components or products that are still useful. There are a number of options for treating a product at end of its first life: extract the energy via combustion, extract the materials, and reprocess them, replace the bits that are worn and sell it again, or, more simply, put it on e-bay or other trading system and sell it as-is.

All have merit. But only one (recycling) can begin to cope with the volume of waste that we generate and transform it into a useful resource. Design for and with recycling will play an essential role in a sustainable future.

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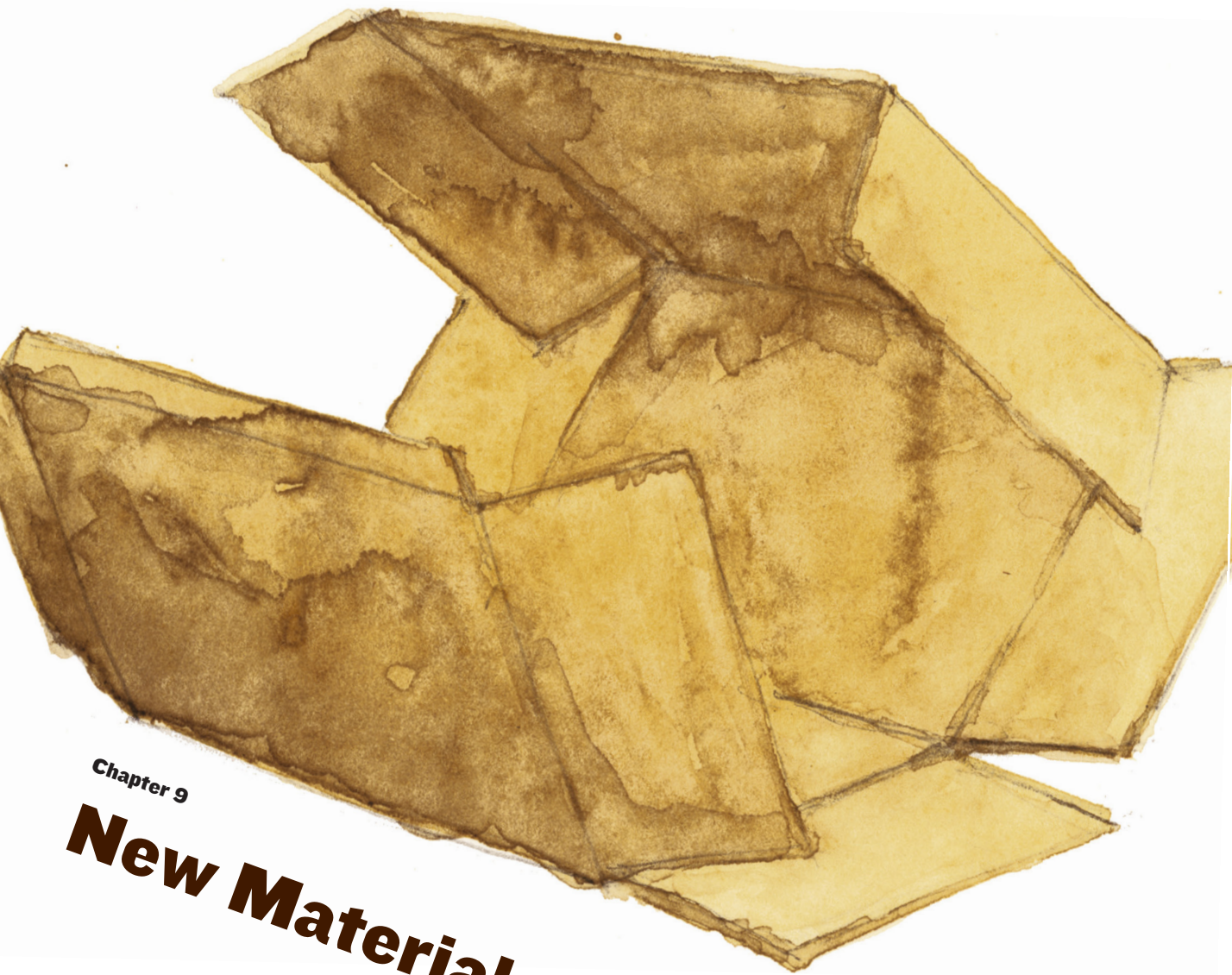
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Chapter 9

New Materials

New materials are often the starting point for designers – they inspire and they can be manipulated to products that had never before seemed possible. It is easy to craft a story around the idea of “high-tech ceramic” or “space-age aluminum” or “advanced composites” – the language of new technologies always seems to build a perception of something new and something better. What is often forgotten is that materials are both personal and technical. And often the challenge in this industry is to remember the human element and not focus only on the technology. This chapter looks at the design opportunities that come from the combination of new materials and design.

“The world seems to expect a never-ending supply of new material options.” That was George Beylerian of MaterialConnexion speaking,¹ and he should know – his company makes its money by peddling information about new materials. Whether the whole world is expectant may be debatable, but designers, certainly, are always on the prowl for what is new. It can be found in several different forms:

- *Materials in research* – electro-active and light-emitting polymers; nano composites, self-healing materials.
- *Materials in early commercialization* – amorphous metals; metal foams; shape-memory alloys.

- *Materials in combination* – wood-filled polypropylene, comingled PP and carbon fibers, ferromagnetic elastomers.
- *Materials in unexpected places* – titanium in eyeglass frames; paper and glass as structural materials, cement furniture, wood as a structural material in electronic equipment (9.1).

1. George Beylerian, MaterialConnexion, New York, NY. www.materialconnexion.com.



9.1 Materials in Unexpected Places

The unusual use of beech for the hand grips of this high-performance camera suggests hand-crafted quality and an exceptional attention to aesthetics (Image courtesy of ALPA of Switzerland).



9.2 A New Metal for Vertu

The casing of these mobile phones (super thin and super strong) are molded from amorphous metal (Image courtesy of Liquidmetal).

New materials have their genesis in the laboratories of universities, governments, and industry. The technologies they develop are spun off, appearing first in “demonstration” products, then absorbed into wider markets. As production volume increases the material price falls, and its increased familiarity to designers and consumers broadens the base of its use. The material progressively approaches a kind of maturity, but can revive its “novelty” by combination with other materials, or by new ways of processing to create composites or hybrid materials – sandwich structures, clad systems, graded or coated structures. The use of an old material in a new setting can make it seem new, restimulating excitement in its potential.

To a designer, a new material offers both opportunities and risks (9.1). Opportunities derive from the new or improved technical or aesthetic behavior that it offers. The risks – and they can be great – lie in the incomplete characterization and the lack of design or manufacturing experience. It is usually the “difficult” time-dependent properties – those relating to long-

term integrity (resistance to corrosion, fatigue, creep, and wear) – that are least well documented and cause the most trouble. There is no historical body of design experience on which to draw, with the result that confidence in the new material is low and investment in it is seen as risky. Channels of communication are imperfect, making it difficult for designers to find the information they want. And, early in life, a new material is expensive – the development costs must be paid for – and availability can be restricted.

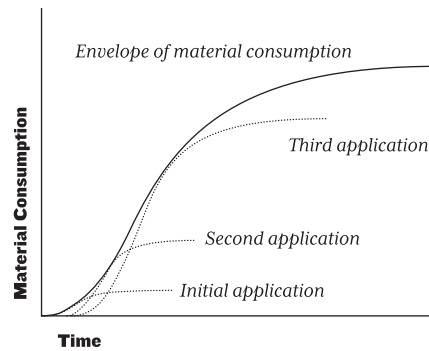
Yet the interest in new materials and processes remains high because success can have a large payoff. Sports products have improved dramatically through the adoption of carbon fiber reinforced polymers, new elastomers, novel sandwich structures and – most recently – the use of titanium and amorphous metal alloys (9.2). Display technology, transformed once by the development of liquid crystal polymers, is about to be transformed again by LEPS – light-emitting polymer films. Advances in medical products have been made possible by new bio-compatible ceramics and polymers; and these, when successful, are very profitable. Hydro-forming and “tailor” blanking of metals, or bladder molding and braiding of polymer-based composites allow shapes that are both material-efficient and aesthetically pleasing. Laser-based processes for cutting and welding give fast, clean joints. An increasing range of rapid prototyping processes allows the designer to realize a concept easily and quickly.

And, of course, there is the excitement – the buzz – that a new material or process can generate both in the mind of the designer and that of the consumer.

The Adoption of New Materials

The success of a new material depends on its ability to attract a sequence of early adopters. The simple picture of materials adoption, sketched as the bold line in 9.3, is in reality the envelope of a set of overlapping s-curves describing a succession of applications of increasing volume. The early applications are in markets that value performance highly and can accept a degree of risk; the later, larger volume applications tend to have the opposite characteristics.

A number of market forces are at work here. Acceptance of risk is associated with a balance between the value of performance and the cost of failure. The nuclear industry values performance but perceives the cost of failure to be so great that, it is sometimes said, no new material will ever be used inside a nuclear reactor – the cost of qualifying it is simply too high. At the other extreme, the sports equipment industry values performance so highly that it seizes eagerly on new materials that are perceived as offering the smallest gain, even when they are imperfectly characterized and may, in reality, offer nothing. And within any one industrial sector there are applications that are more or less risk sensitive. Thus the successful introduction of



9.3 Material Consumption over Time

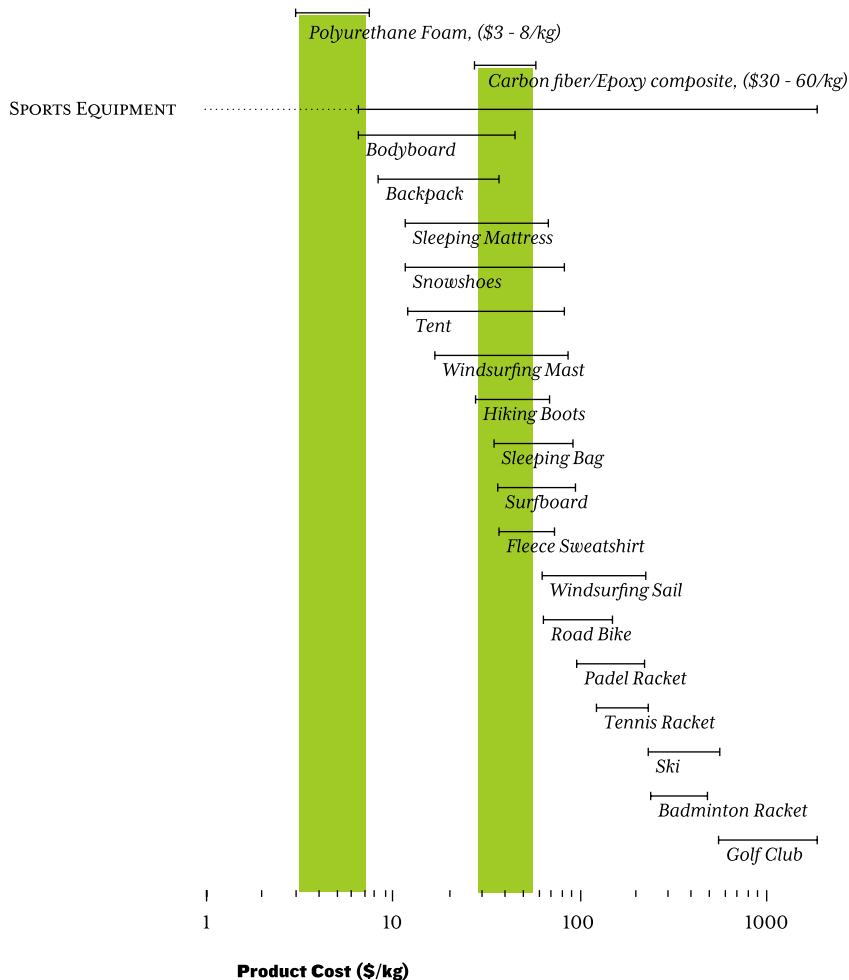
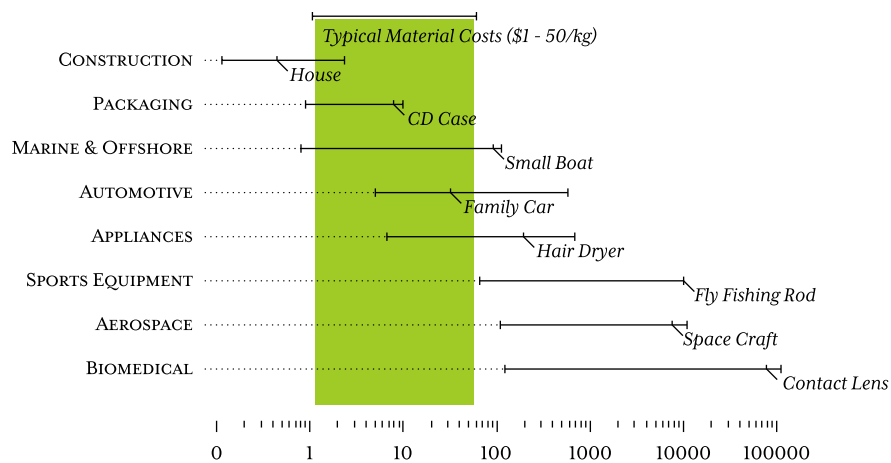
The entry of a new material into the market requires a low volume, performance-driven opportunity that is not risk-averse.

polymer-matrix composites in aerospace was initially confined to non-critical components; only now (in 2009) is an all composite wing for a large civil aircraft a reality. In civil engineering, the use of advanced materials, such as PTFE-coated glass-fiber roof membranes, is limited both by cost and by uncertain long-term durability to buildings in which the dramatic spatial possibilities they offer outweigh the risk of possible failure.²

At this point it is useful to introduce the idea of *material-cost sensitivity* (9.4).

The cost of a golf tee is little more than twice that of the material from which it is made; the value-added in manufacturing is low. If material cost doubles, the cost of the golf tee must rise significantly; the product is material-cost sensitive. At the other extreme, the cost of a golf club can be as much as 20 times that of the materials that make it up. Here a doubling of material costs increases the product cost only slightly; the value-added is high and the product is material-cost insensitive. New materials are most readily adopted in industries that are material-cost insensitive: high end appliances and automobiles, sports

2. London's Millennium Dome and the Schlumberger building in Cambridge (shown in 6.2k) are examples.



9.4 Material-Cost Sensitivity
(top) Product cost per kg across a number of industries; (bottom) details for the sports equipment industry.

equipment, aerospace and biomedical equipment (try the calculation³ for a brand-named toothbrush!).

Among these, the sports equipment industry is one of the most receptive and most visible – a good combination when seeking showcase products for a new material or process. Fiberglass, first developed for radar nose cones for WW11 aircraft, quickly displaced wood in boat hulls and surfboards and found further applications in high-profile designs like the chairs of Charles and Ray Eames (1950). Carbon fiber/epoxy and metal matrix composites, titanium and high strength aluminum alloys, all developed with defense and space applications in mind, are better known to the average consumer for their use in clubs, racquets, and bicycle frames. From there they spread out into other products – watches, lightweight computer housings, furniture, kitchen and bathroom equipment. Materials research, motivated in the past by military and aerospace applications, is now directed more at the consumer than before, giving the designer – and in particular the industrial designer – significant influence. The adoption of translucent polycarbonate for the housing of the iMac and of titanium for that of the iBook – examples of one company's use of old materials in new ways – creates new markets for the materials themselves, and at the same time brings them to the attention of designers of other products.

But the challenges remain. We focus on two: the information void encountered by product designers seeking to use new materials and the difficulty designers have in stimulating suppliers

to develop materials with the attributes they want. Central to this is the task of communication, both from developer to designer, and in the opposite direction.

Information about New Materials

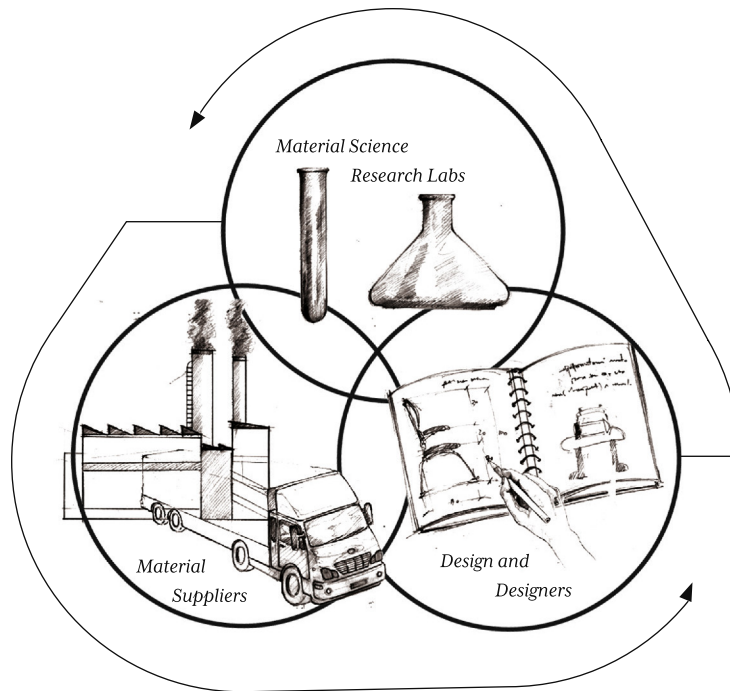
Most new materials for design emerge through the commercialization of research, that is through science-driven development (9.5). The developer communicates information about the material through advertising, press releases, profiles, and datasheets. The communication, if successful, stimulates designers to use the material in creative ways. But for this to work two things are necessary. The first: that the information includes that required for product design – and as we know, that means much more than just technical attributes. And second: that the language in which it is expressed has meaning both for the supplier and the designer, requiring a vocabulary to express design requirements and material behavior that both parties can understand. If information is flowing in the forward direction, it can also flow back: the designer influences the development of materials by suggesting or requesting specific technical, processing or aesthetic behavior.

The need, then, is one of communication. The usual information sources for new materials – press releases, supplier datasheets, producer catalogs – report what is good about them but seldom what is bad, and they generally focus on technical attributes. The attributes that

3. A toothbrush weighs roughly 10 grams, can cost up to \$5, and typically, is made of polypropylene or PMMA with nylon bristles. These materials cost between \$1 and \$3 per kilogram.

9.5 Positive Feedback

The interaction of materials research, suppliers, and designers.



4. *Antonelli (1995)* catalog of the MOMA exhibition “Mutant Materials,” *Juracek (1996)* book of images and textures and *Manzani’s (1989)* book “Material of Invention” are examples. The New York-based consultancy *MaterialConnexion* provides a material information service for industrial designers. The consultancies listed in Chapter 2 provide material collections and material information services for industrial designers.

5. *Manzani (1989)*.

bear on industrial design are far harder to find, with the consequence that materials that are technically familiar are often unknown to the industrial designer. Here the need is for visual and tactile attributes – those that help create the associations and perceptions of a product. The desire to fill this need motivates occasional exhibitions, books, and services⁴ but some of these are not easily found and none provide structured methods of selection. An example of the information that one of these offers is shown in 9.6. It describes the technical or perceived attributes of a new material – a metal foam – hinting at the possibilities of energy absorption and lightweight design.

Vague rhapsodies about the wonders of a new material can serve to stimulate interest, certainly. But if you want

to design with the material you need to know the bad news as well as the good. Metal foams provide a case study. What does a metal foam cost? (A lot.) Does it corrode easily? (Yes.) Is it easy to shape? (You can cast it and machine it but not much else.) Are there any commercially successful consumer applications?

(Not yet.) And – since you want to make something out of it – what is its strength? Its thermal conductivity? The datasheet doesn’t tell you. Emerging materials can have an awkward adolescence during which their true character only slowly emerges. Mature materials are familiar in all their aspects. Manzini⁵ cites the example of wood: it has been touched, smelt, bent, broken, cut, strained, stressed, dried, wetted, burned, and maybe even tasted by most humans; we know what wood is and what it

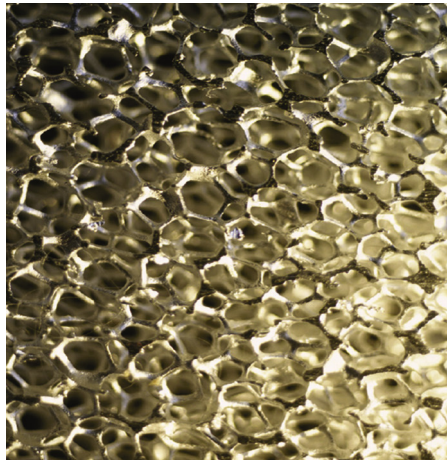
does. A new material is not embedded in the designer's experience in the same way. We need a way of assembling and communicating information about it that paints a fuller picture of its emerging character. As the designer Richard Seymour puts it, *"We need a system where the technology can meet the application. Where materials manufacturers can propagate their ideas directly to the very people who can apply the necessary imagination to utilize their properties."*⁶

What can be done? Two possibilities are explored here. The first is to develop profiles of new materials in a more complete form, attempting to capture both technical and aesthetic attributes. The second is the idea of material workshops – direct interaction between those who make and characterize materials and those who design with them.

Profiles for New Materials

The material profiles of the latter section of this book have a standard format, reporting technical, perceived and visual behavior, design guidelines, and typical uses. For *new* materials some of this information is missing – most notably, guidelines for design and established uses. It is still possible to assemble much of the rest, and even to indicate where applications might lie. Three examples are given at the end of the reference for material profiles; they are *metal foams*, *amorphous* or "glassy" *metals*, and *shape-memory alloys*.

There is enough information in these profiles to plot them onto the material property and MDS maps described in



Chapter 4, allowing them to be compared with the "world" of materials. On the stiffness and density map shown in Figure 4.4, metal foams lie above rigid polymer foams – a little heavier and a little stiffer – and of course, they can be used at higher temperatures and are much more durable.⁷ The same can be done with MDS maps, and here, too, there are interesting insights. Plotting them on the MDS map shown in Figure 4.5, we find that they lie closer to woods and to ceramic foams than to polymers – a perception that led a researcher to liken the material to "metallic wood."

The comparisons are enlightening, suggesting possible applications of metal foams that exploit their stiffness and low weight and their ability to absorb energy, found by pirating applications of polymer foams or of woods in which additional durability or high temperature performance is wanted: cores for sandwich panels, lightweight fire-proof partitioning, and certain sorts of packaging.

9.6 Introducing a New Material

Aluminum foam description from Materials and Ideas (Material Connexion): The process of aluminum foaming combines powder aluminum with a foaming agent and produces complex shaped foam parts, metal foam sandwich panels and foam-filled hollow profiles. The parts have a closed cell microstructure and a high fraction of porosity (40–90%), with a relatively homogeneous and isotropic pore structure. The foam has a high specific stiffness-to-weight ratio, high impact and energy absorption, and high thermal and acoustic insulation. In automotive applications, it is used as a rewall behind the engine, and as the autobody structure, which promotes reduction in weight and thus savings in fuel. The process of foaming metal can therefore lead to new developments in structural furniture construction for the foam's strength and lightweight properties.

6. *Richard Seymour (1998) writing in "winning the design of sports."*

7. *The same thing can be done using the other eight material property charts in the Appendix at the end of this book.*

A Material Workshop

The challenge of communication can be addressed in another way – that of a workshop bringing together experts who have developed and characterized the material with the designers who wish to use it. We have tried a number of these, most recently organizing a meeting at SeymourPowell, London (a design consultancy) attended by three materials scientists and four designers. The materials people presented a portrait of the material – aluminum foams again – using samples of metal foams and material property charts to put it in context, addressing the questions:

- *What is it?*
- *What processing possibilities and limits exist?*
- *What is its character?*
- *How does it behave?*
- *What are the competing materials?*
- *Where has it been used before?*
- *Where -from a technical viewpoint – might applications lie?*

This stimulated a brainstorming session in which the designers took the lead, seeking technical information from the materials people when needed. All of the technical applications referred to earlier were explored. The visual aspects of the material, particularly, intrigued

the designers – open-cell foams look opaque and solid in reflected light, but they transmit light when back-lit. This, and the interesting natural textures of the skinned foams, suggested applications in light fixtures, furniture, as loud speaker casings (exploiting its damping characteristics) and as architectural paneling.

Meetings like this break down many barriers and open channels for communication of a sort that even the best profiles cannot achieve.

Material Exploration

If it is the role of the designer to see possibility in new materials, to find meaning that is relevant to people, to enable the creation of new experiences, then materials are often a good starting point. New materials and “old” can be manipulated and modified in order to create design expressions that communicate what is unique about that material. At first, it is important to understand the unique attributes that a material offers. In the end, it is important to create strong, visual descriptions of what is possible. These images can be used to inspire designers, investors, or clients. The ability to experiment on your own and inspire others to experiment with an exploration of materials (new and old) is an important skill for a designer to learn. Included here are a few case studies from IDEO (www.ideo.com) that show a range of material exploration and design expression: Vision, Heat, LiquidMetal, and Fabrications. The first two case studies explore the attributes of different



types of plastics – with names that are probably unfamiliar to most designers (even the more seasoned). Plastic is one of those materials that is sort of defined by its ability to be easily manipulated, to serve any function or decoration. But here we look closely at what design is possible with two specific plastics.

The second two case studies explore the attributes of two materials that have each defined entirely new categories. It is these materials that are often expected to lead to immediate innovation, but success in using a new material requires a subtle understanding of technical attributes, aesthetic possibility, and human behavior.

Eastman Plastics

This project was called “Vision”; it is an exploration of the unique attributes of two more plastics – cellulose (a plastic that is made from polymerized cotton and wood pulp) and copolyester (PETG or glycol-modified polyethylene terephthalate). The design team was looking for ways to reinterpret known materials. Future advancements in design will rely strongly on close collaboration between designers and materials suppliers.

In this exploration, IDEO and Eastman explored new and ingenious designs with two of the materials Eastman manufactures, copolyester and cellulose. These materials are known but their possible incarnations are far from exhausted. The unique nature and behaviors of these plastics presented exciting opportunities and challenges for IDEO’s designers. The exploration was both symbiotic and satisfying and the result celebrates the rediscovery of copolyester and cellulose.

The design team built a series of contemporary design stories around the theme of eyewear. Each story inspired a concept that was implemented in either cellulose (9.7a) or copolyester (9.7b). It was the design intention to capture the effort and emotion behind the exploration in materials and design and then present it to a wider audience.

BASF High Temperature Plastic

This project was called “Heat”; it is an exploration of the unique attributes of high temperature plastic, in particular the focus was on one material (polyphenylsulfone, which is sold by BASF

Figure 9.7 Cellulose and Copolyester

*Eyewear inspired by plastic
(Image courtesy of IDEO).*



9.8 Polyphenylsulfone

Consumer appliances inspired by technology (Image courtesy of IDEO).

with the brand name “Ultrason”). The design team was inspired by the unique attributes of the material and focused on creating a family of household objects: a kettle, a toaster, a clothes hanger, a lamp, and a hairdryer.

The kettle (9.8a) allows you to watch the water as it boils in a clear, cool-to-the-touch plastic double-walled container, which can be placed directly on any surface after heating. A metal plate at the bottom heats the water by induction, making it safer and easier to clean. The toaster (9.8b) is a soft-edged and lightweight form. Its open and transparent structure allow for a visual and olfactory sensory experience, and prevents burning by allowing the cook to directly control the appliance by sight. The hanger (9.8c) brings together the iconic forms of wire coat hangers and t-shirts to hang, dry, and warm shirts.

It applies heat and tension to smooth wrinkles, effectively eliminating two stages of laundry tedium. The heat is created by an induction bar that heats a thin filament along the exterior edge. The lamp (9.8d) is made from a single piece of plastic. The bulb can be screwed

directly into the plastic, distilling the design to its most minimal form. It can stand on a table or act as a pendant light. The hairdryer (9.8e) foregoes a handle, making it smaller and lighter – for travel. The emphasis on portability is reflected in the smart wrapping and plugging of the cord. The design can be produced in a one-step molding process, with integrated air vents and no visible part lines.

Liquidmetal Amorphous Alloys

Liquidmetal® is a new metal alloy that competes with plastic and ceramic in a way that was previously difficult for metals. The material, a combination of titanium, beryllium, copper, nickel, and zirconium, is cast by a process that allows surface finish and detail equal to or better than that of injection molding plastics. Due to hardness values that are close to that of ceramic, it can achieve and maintain a mirror finish, with the possibility that details can be formed at a micron level. Finally, its mechanical properties as part of a thin-walled structure make it a superior spring or an integral (or living) hinge.

9.9 LiquidMetal

The possibilities created by new metal structures (Image courtesy of IDEO).



In order to manipulate these attributes, the material was represented as the surface and structure of a slim mobile phone (9.9). The phone was designed to fold without a separate hinge. Other concepts included a metal Ziploc-like bag fastener and flexible metal perfume packaging.

Eleksen Electronic Fabric

This project started as a material exploration of the unique attributes of a smart fabric that could sense location in three-dimensions – that project was called “Fabrications”. The fabric combines conductive fibers in a traditional weave. The final deliverable was a fabric keyboard that could also serve as a protective case for the PDA (9.10). Eleksen makes the material, Logitech makes the keyboard – KeyCase. These products were popular when PDAs were popular and have been in some ways made temporarily obsolete by the ease of typing on the QWERTY or T9 keyboards on your mobile phone or smartphone.

To begin working the user merely unfolds the keyboard and attaches it to the device, which activates the keyboard. The keyboard is comfortable to use in any context or against any surface. Users can control behaviors like scrolling or repeat actions by pressing down longer. The keyboard is made of silicone and fabric; it is tough enough for daily use and can be easily cleaned. It weighs less than five ounces, and is only five millimeters



9.10 Fabrications

A fabric that is functional, surprising and convenient. (Image courtesy of IDEO.)

thick. It could almost be used as a pillow after a late night of computing.

Conclusions

It is often difficult to get information about new materials and certain industries are quicker to adopt new materials than others but it is actually the designer that has the most influence here. Designers who want to get inside the factory, explore new technologies, talk to material scientists, and ask questions, are the most successful. New materials are just the starting point, there are many possible applications in product design: unexpected surfaces, unique experiences, simple functions, or meaningful behaviors.

Further Reading

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Juracek, J.A. (1996) "Surfaces, Visual Research for Artists, Architects and Designers," Thames and Hudson, London, UK. ISBN 0-500-01758-1. (An intriguing compilation of images of textured, weathered, and deformed surfaces of hundreds of materials.)

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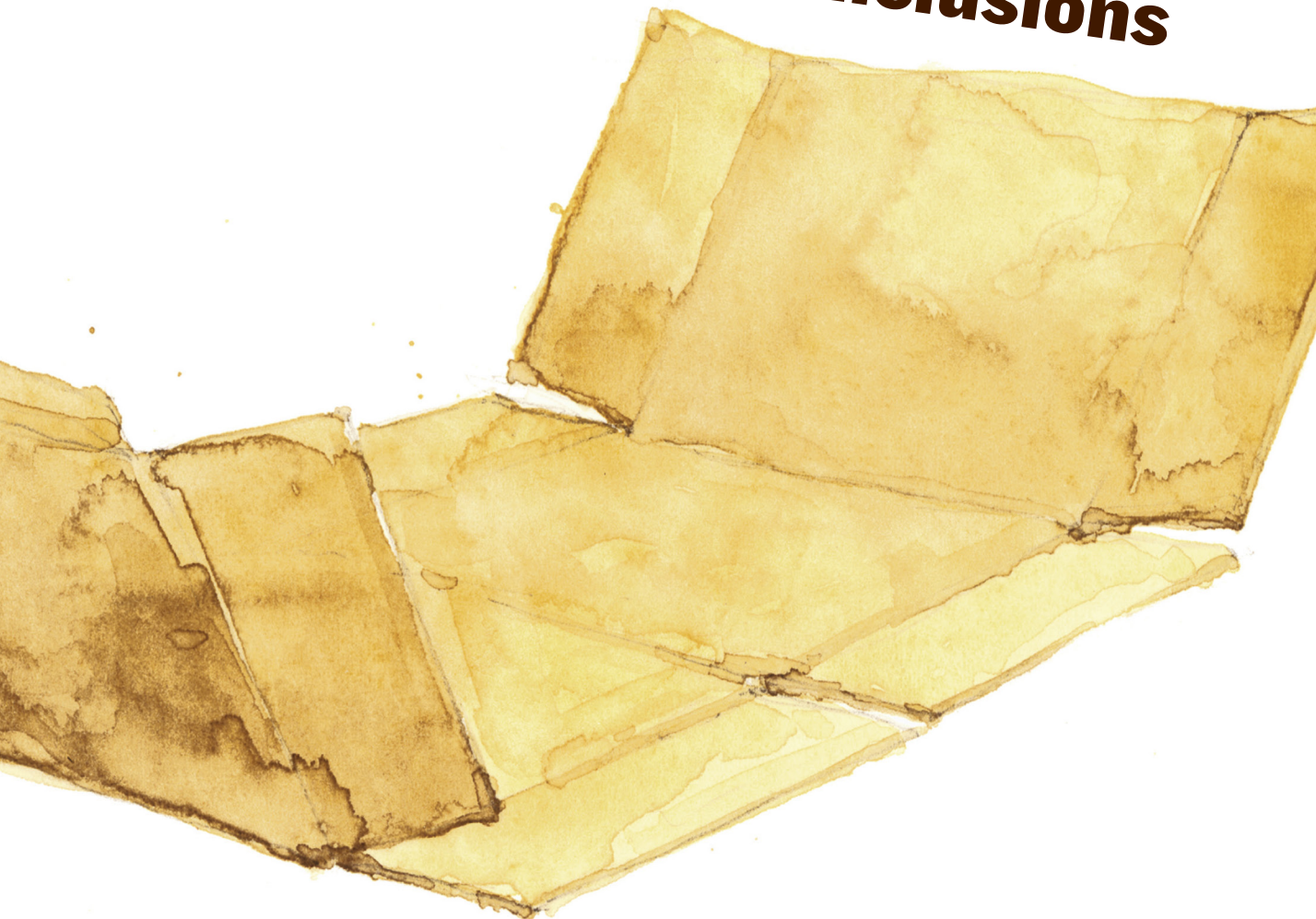
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MaterialConnexion (2001) A New York-based materials information service (www.MaterialConnexion.com).

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Chapter 10

Conclusions





Inspiration - the ability to stimulate creative thinking - has many sources. One of these is the stimulus inherent in materials. It is one that, since the beginning of time, has driven humans to take materials and make something out of them, using their creativity to choose function and form in ways that best exploit their attributes. The most obvious of these attributes are the engineering properties - density, strength, resilience, thermal conductivity, and such; it is these that enable the safe and economical design of products. The enormous economic importance of technical design in any developed

society has given material and process development to meet technical needs a high priority; there are established methods to select them, widely taught and extensively documented in texts and software. But a material has other attributes too: color, texture, feel, a sort of "character" deriving from the shapes to which it can be formed, its ability to integrate with other materials, the way it ages with time, the way people feel about it. These, too, can stimulate creativity - the kind of creativity that gives a product its personality, making it satisfying, even delightful.

We have sought, in writing this book, to draw together lines of thinking about the selection of materials to serve both technical and industrial design. Selection for technical design is the subject of the companion volume; here the emphasis is more heavily on the second. What do we learn? First, that a material has many dimensions: a technical dimension, the one seen by the engineer; an economic dimension, its role in adding value to products; an eco-dimension, that seen by the environmentalist; an aesthetic dimension, the one encountered by the senses of sight, touch, hearing; and a

dimension that derives its features from the way in which the material is perceived, its traditions, the culture of its use, its associations, its personality.

Attributes of aesthetics and perception are less easy to pin down than those that are technical, yet it is essential to capture them in some way if their role - and it is obviously an important one - is to be communicated and discussed. There are words to describe visual, tactile, and acoustic attributes; they can even, to some extent, be quantified. Perceptions and emotion are more difficult. A few, perhaps, can be identified - gold is, almost universally, associated with wealth, steel with strength, granite with permanence, plastics with the modernity... well, even these are uncertain. The way we think about materials or materiality depends on context, culture, demographics, style, trend, and more. It is difficult for people to talk directly about the materials that are used to make the stuff they buy, it is the role of the designer to express the materiality of each object. This materiality is how we build tangible connections between the brand that is represented, the object that is created, and the experience that is enabled. So, we conclude: materials have an intrinsic personality, but one that is hard to see until brought into sharp focus by product design that is intended to tell a story. The story must be relevant and meaningful to consumers, it is made real by the materials and manufacturing processes that inspire us and then are specified.

The first step in product design is that of identification of a concept, a new idea, the design principles on which

the product will be based. In the second - visualization - the desired features are developed, using sketching, model-making, and computer graphics to sharpen the constraints on configuration, size, functionality, and personality, as described in Chapter 6. It is in the third - materialization - that the choice of materials and processes is made, prototypes built and tested, and the final design agreed.

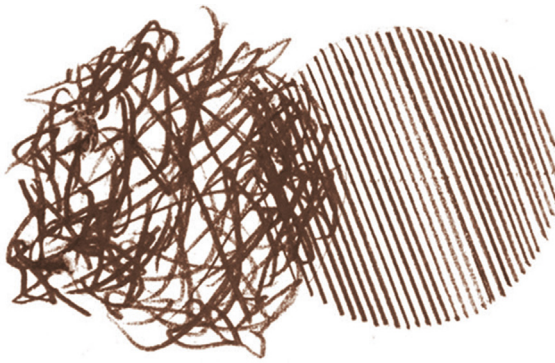
This choice is guided not only by technical requirements but also by requirements of aesthetics, perception, emotion, and personality. To achieve it we need selection methods that are flexible and can deal fluently with information of many different types. This reasoning led to the information structure introduced in Chapter 7. A material can be characterized by its name, its technical and aesthetic attributes. It can be indexed, so to speak, by the processes able to shape it and by products in which it is used. Products are designed with certain broad intentions in mind. These intentions influence every design decision, including the choice of materials; thus materials can be linked to design intention through products. Products also have aesthetic and perceived attributes that are a deliberate part of the design, materials can be linked to these too. And the experiences we have with products create emotional attributes and the personality of a material. For materials, this is not the only way to organize the information product designers need, but it is one that works - it is both practical and inspirational. It is helpful to see materials within the context of the structures

and surfaces that we know and understand from the world of products - the stuff that surrounds us. As a structure for material selection, this allows a range of methods.

Product design has a technical component and this is of vital importance - no one wants a product that does not work; established methods of analysis deal with this. Analysis is of less help in selection to meet the other aspects of design (industrial or product design) - these are too heavily dependent on how we think about the senses (visual, tactile, acoustic) and perceived attributes (emotion, personality). In this case, methods using judgments of similarity, analogy,

or simply directed curiosity ("browsing") are more productive.

The path from design requirement to product specification is rarely linear; almost always it is devious, assembling bits of information by one method, other bits by others, and combining them into a solution that - although based on existing information - can be entirely new. There is structure in it, but there is a degree of chaos too (10.1). Without structured methods, material selection gets nowhere. But without a little craziness and chaos, the really novel solutions may be missed. Balancing structure and chaos is key to innovative material selection.



10.1 Structure and Chaos

Balancing structure and chaos is a component of innovative material selection.

Appendix: Selected Material Maps

CHART 1 – Elastic Modulus/Density	200
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The six charts shown here are maps of technical attributes. They show the islands and continents, so to speak, that are occupied and the oceans in between that are empty. Parts of these oceans can be filled by making composites, sandwich structures, and other configured materials (foams, for instance) that combine the properties of two or more single materials – there is still uncharted water here. Other parts cannot be reached at all, for fundamental reasons to do with the physics of the way in which atoms are bonded in solids. The charts form part of a larger set that can be found in the companion text (Ashby, 2005); they were constructed using the CES Edu (2009) software. Some of the labels have been shortened for the sake of space: thus, tsPolyester is thermosetting polyester, tpPolyester is thermoplastic, and elPolyester is elastomeric; fPU is a flexible polyurethane foam, rPU is rigid foam, sPU a structural foam, oCPU is open cell, and ccPU is closed cell.

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Chart 1 – Elastic Modulus, E, and Density, ρ

If a solid is deformed elastically, it springs back to its original shape when released. The atoms of solids are held together by atomic bonds – think of them as little springs linking the atoms. If the springs are hard to stretch, the solid is stiff; if they are easy to stretch, the solid is compliant. Young's modulus is a measure of the stiffness or compliance of the bonds. Metals and ceramics are stiff; polymers are much more compliant. Foams and elastomers are even more compliant, and for a new reason: their structure allows additional deflection (cell wall bending, molecular rearrangement) which, nonetheless, is recovered when the loads on the material are released.

Interatomic spacings in materials do not vary very much: they are all within a factor of 3 of 0.3 nm (3×10^{-10} m). The densities of materials – the mass per unit of their volume – vary far more widely, simply because some atoms are heavy (copper, iron – and thus steel) and others are light (hydrogen, carbon – and thus polymers like polyethylene, $(\text{CH}_2)_n$).

Chart 1 – Elastic Modulus and Density

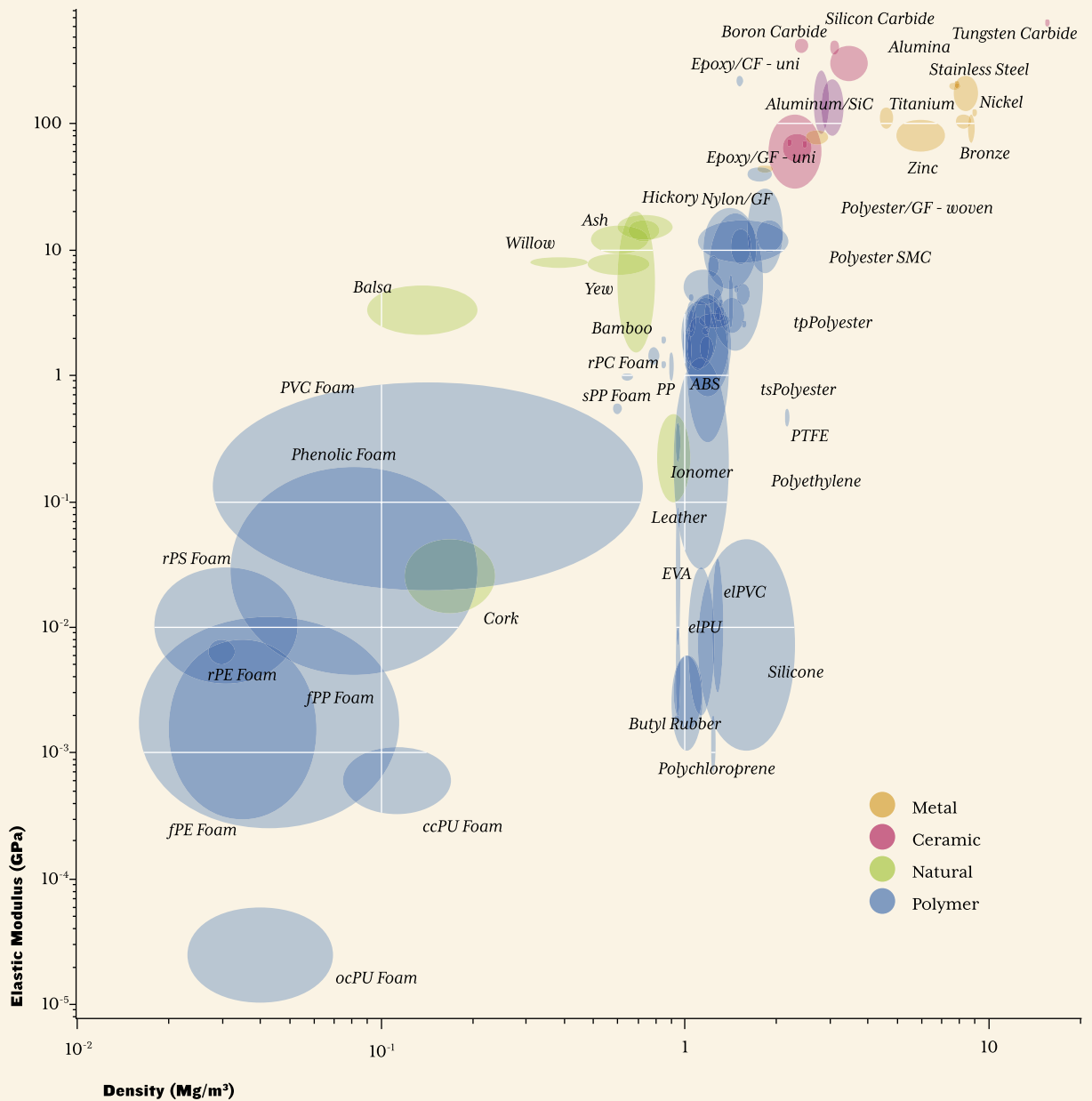


Chart 2 – Strength, σ_y , and Density, ρ

Strength is different from stiffness – think of it as a measure of the force needed to break atomic bonds. In brittle materials (glasses, ceramics) breaking means just that: the solid fractures. But in ductile materials (metals, many polymers) the bonds break, the atoms or molecules move, and new bonds form, leaving the material just as it was before, but with a new shape. This ability to reform bonds gives ductility and thus the ability to be shaped by rolling, drawing, molding, and stretching.

“Strength,” here, means the 0.2% offset yield strength for metals. For polymers it is the stress at which the stress-strain curve becomes markedly non-linear – typically a strain of about 1%. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile fracture strength. For composites it is the tensile strength. For elastomers it is the tear strength.

Chart 2 – Strength and Density

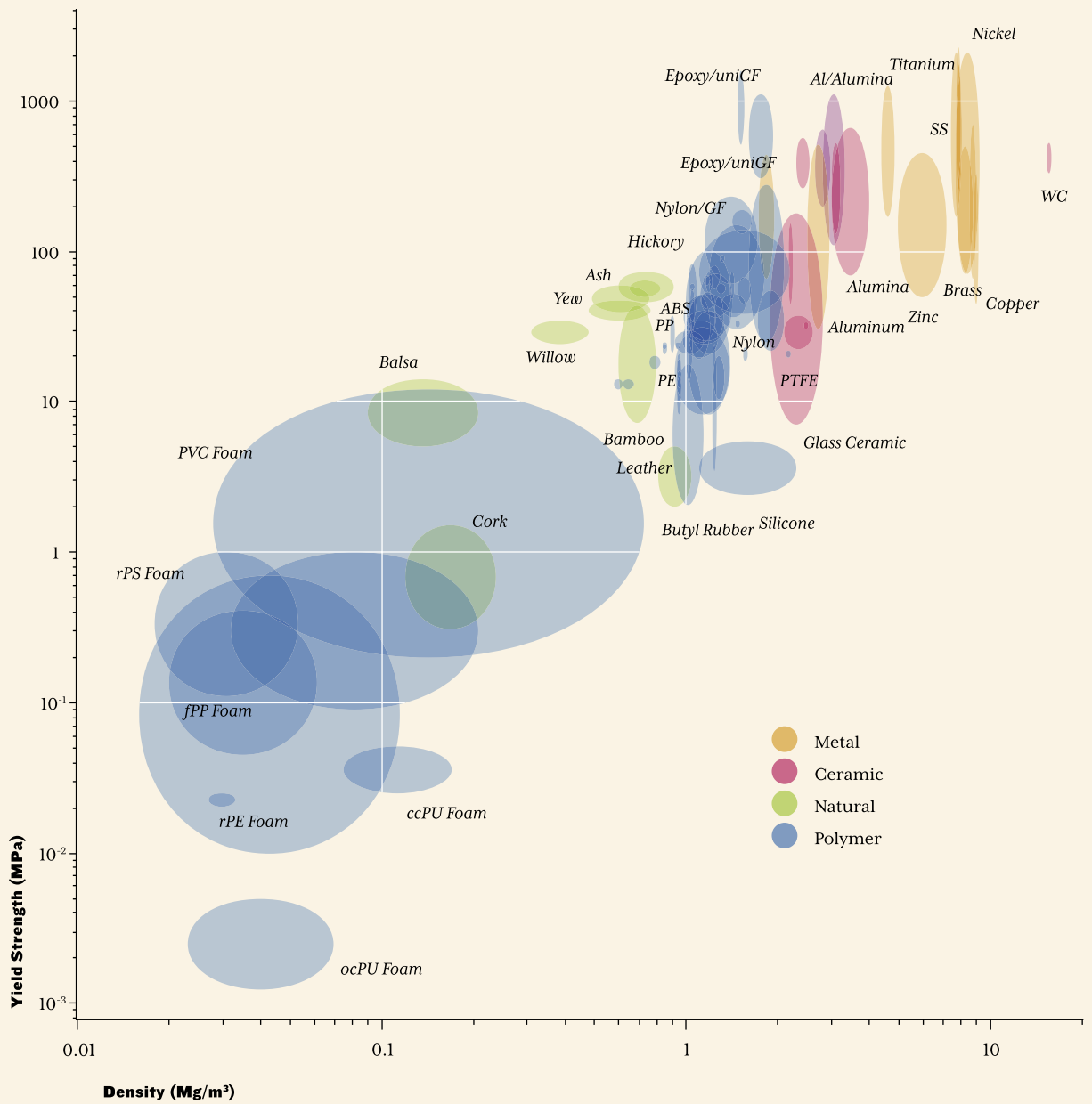


Chart 3 – Fracture Toughness, K_{IC} , and Elastic Modulus, E

If you nick the edge of a cellophane wrapper or scratch the surface of a plate of glass, it will crack or tear from the nick or scratch. If you do the same to copper or steel, it won't. That is because the first two have low fracture toughness, K_{IC} , the property that measures the resistance to the propagation of a crack. Materials with low fracture toughness are strong when they are perfect (that's why it's so difficult to get the cellophane wrapper off a new CD or packet of biscuits), but as soon as the surface is damaged they break easily. Materials with high fracture toughness are crack tolerant; they still carry loads safely even when cracked. The chart shows fracture toughness, K_{IC} , plotted against modulus E . The "toughness," G , is related to K_{IC} by $G = K_{IC}^2/E$ – shown as a set of diagonal contours.

Chart 3 – Fracture Toughness and Elastic Modulus

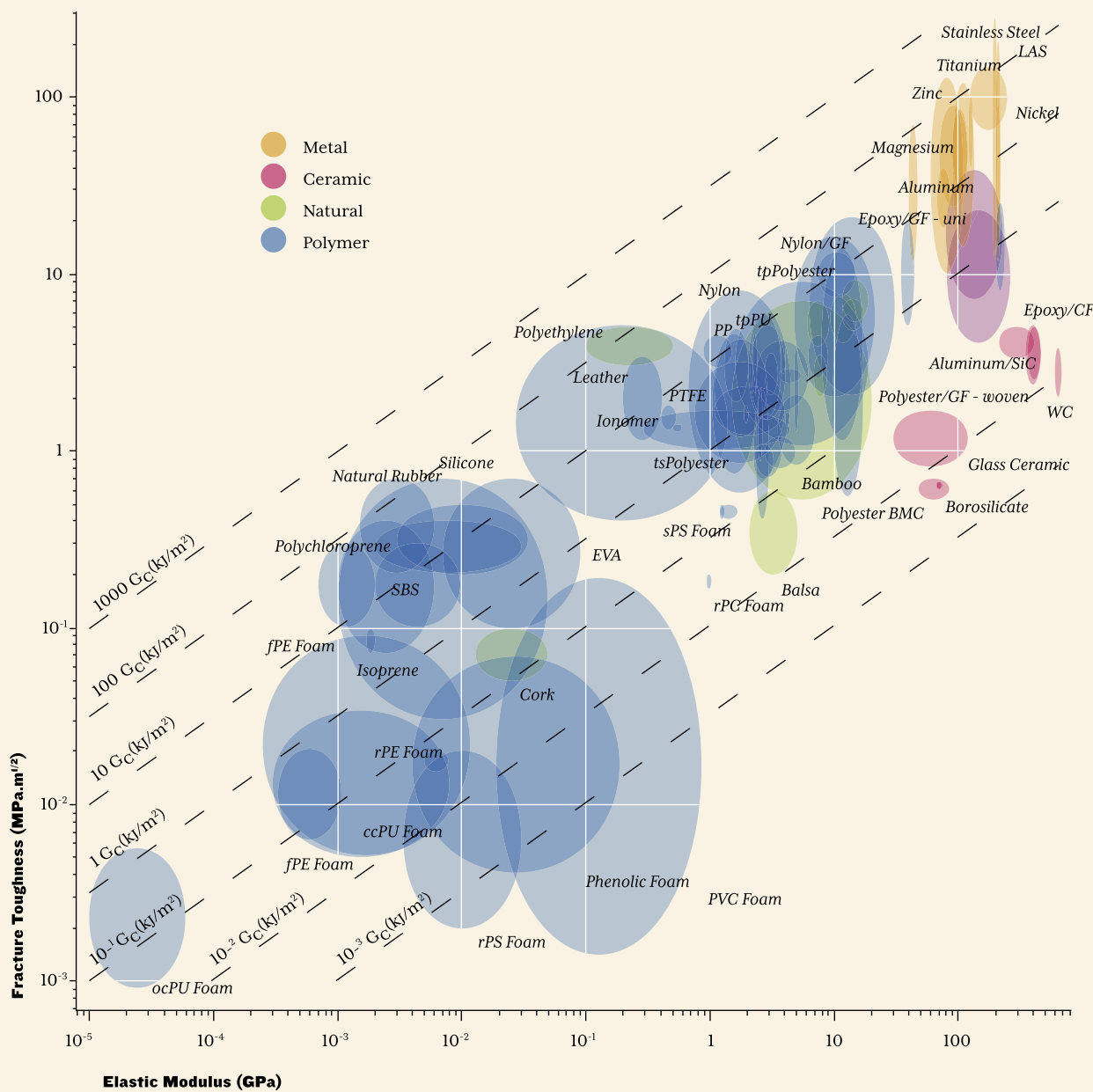


Chart 4 – Elastic Modulus, E , and Strength, σ_f

There are no new properties here. The value of the chart is that many designs depend on one or another combination of E and σ_f . Thus resilience – the ability to bend without damage (like leather) is measured by the combination σ_f/E , shown as one set of contours on the chart. The ability to store and return elastic energy (something rubber is good at) is measured by σ_f^2/E (not shown). Materials with large values of these combinations perform well in these functions.

Chart 4 – Elastic Modulus and Strength

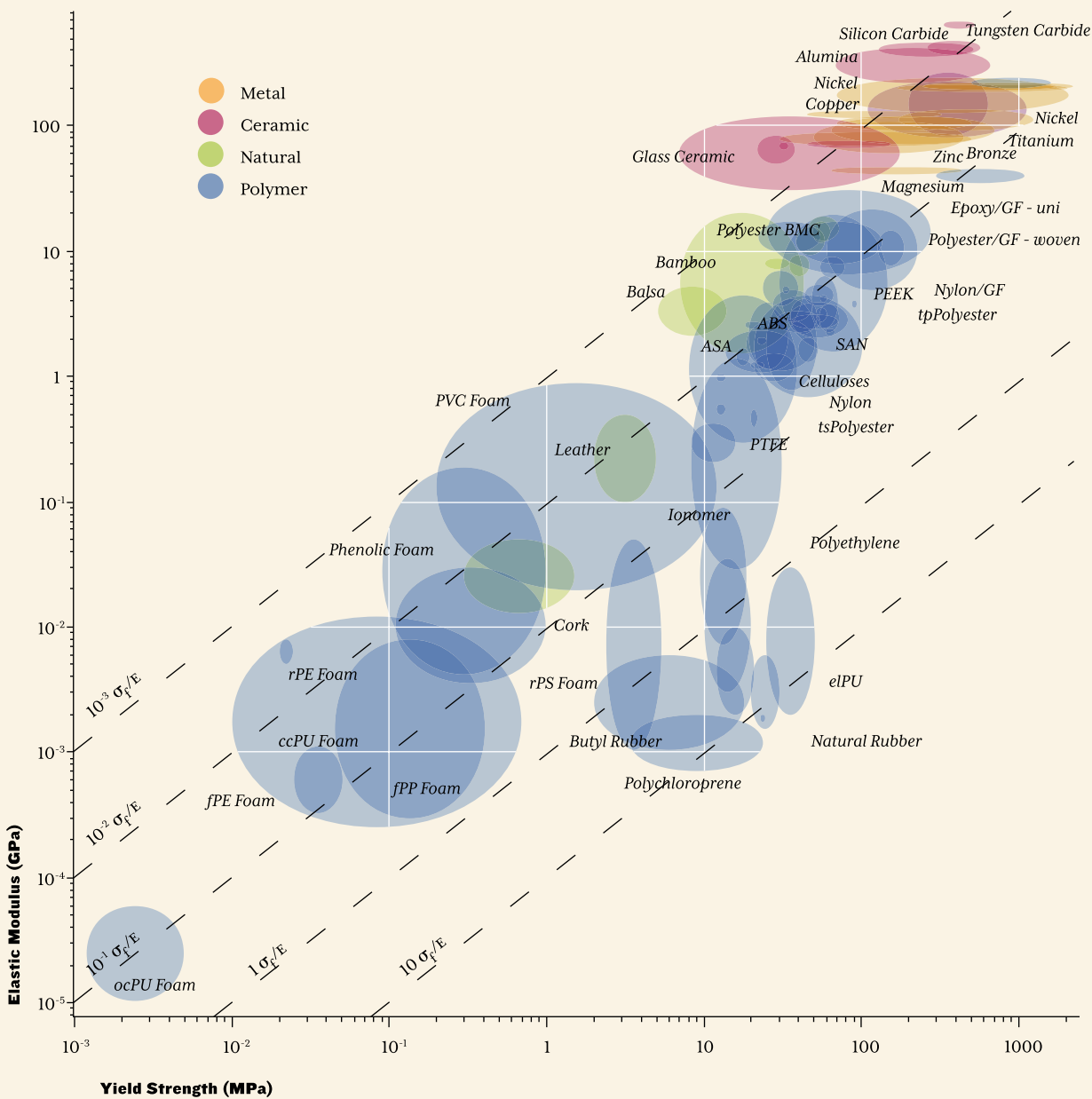


Chart 5 – Loss Coefficient, η , and Elastic Modulus, E

If a hard steel ball is dropped onto the surface of a material, it bounces back. The height to which it bounces is a measure of the loss of energy in the material: the higher it bounces, the less is the loss. Low loss coefficient materials return almost all the energy of the ball so that it will bounce many times (as many as 1000) before it comes to rest. High loss materials bring the ball to rest almost immediately. Choose low loss materials for springs, vibrating reeds, strings for musical instruments, and precision suspension systems; choose high loss materials for vibration damping.

Chart 5 – Loss Coefficient and Elastic Modulus

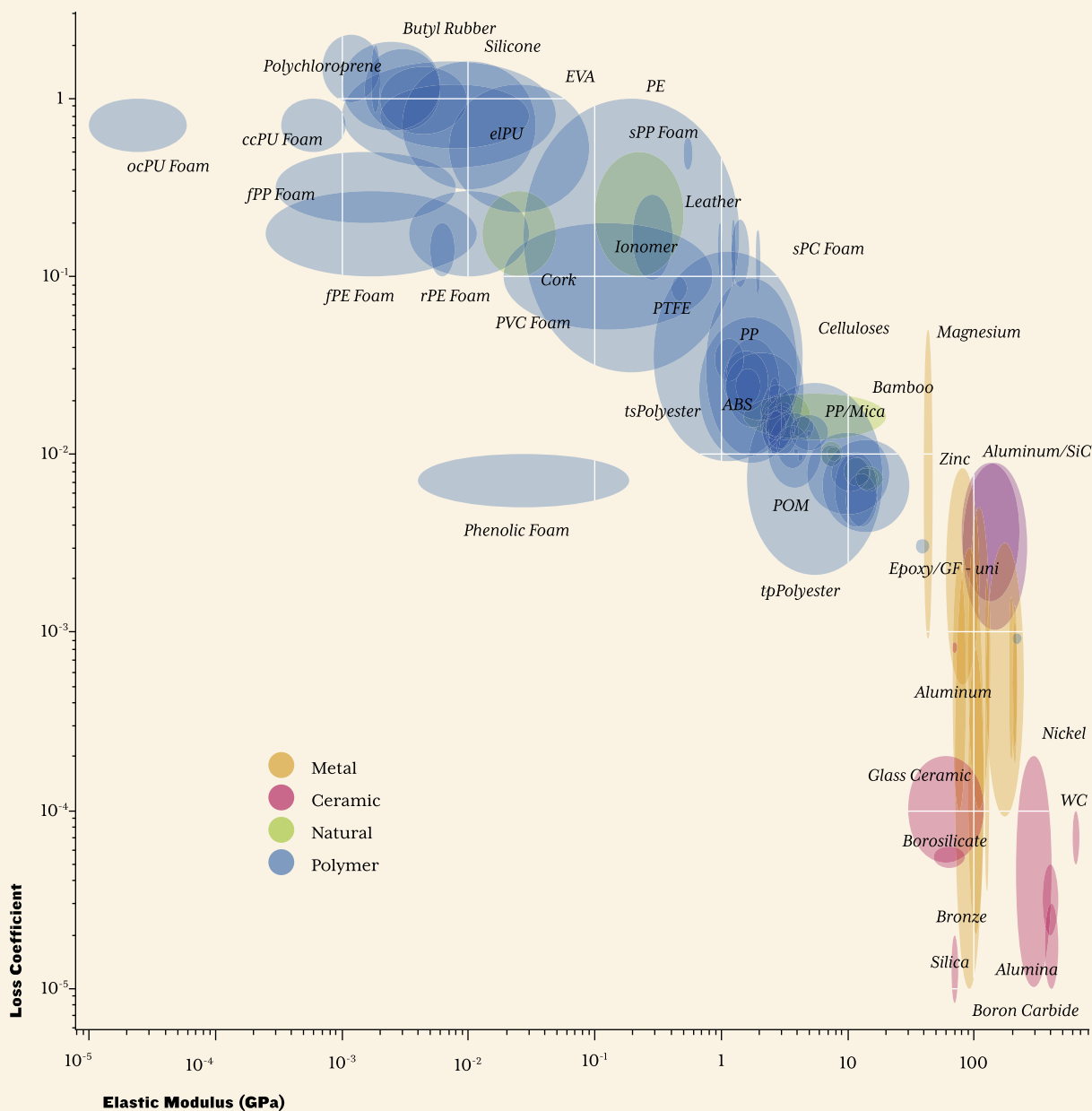


Chart 6 – Thermal Expansion Coefficient, α , and Thermal Conductivity, λ

Expansion and conductivity are the two most important thermal properties of materials for product design. They vary greatly: the chart shows that metals and certain ceramics have high conductivities together with low expansion. Polymers and elastomers have conductivities that are 1000 times less, and they expand at least 10 times more. It is important to match expansion coefficients when joining different materials that will be used at high temperature; if this is not done, damaging stresses appear when the temperature is changed. High thermal conductivity is valuable in heat exchangers and heat sinks, and when a uniform temperature is required (as in a cooking vessel). Low conductivity is valuable when the aim is to insulate against heat.

Chart 6 – Thermal Expansion Coefficient and Thermal Conductivity

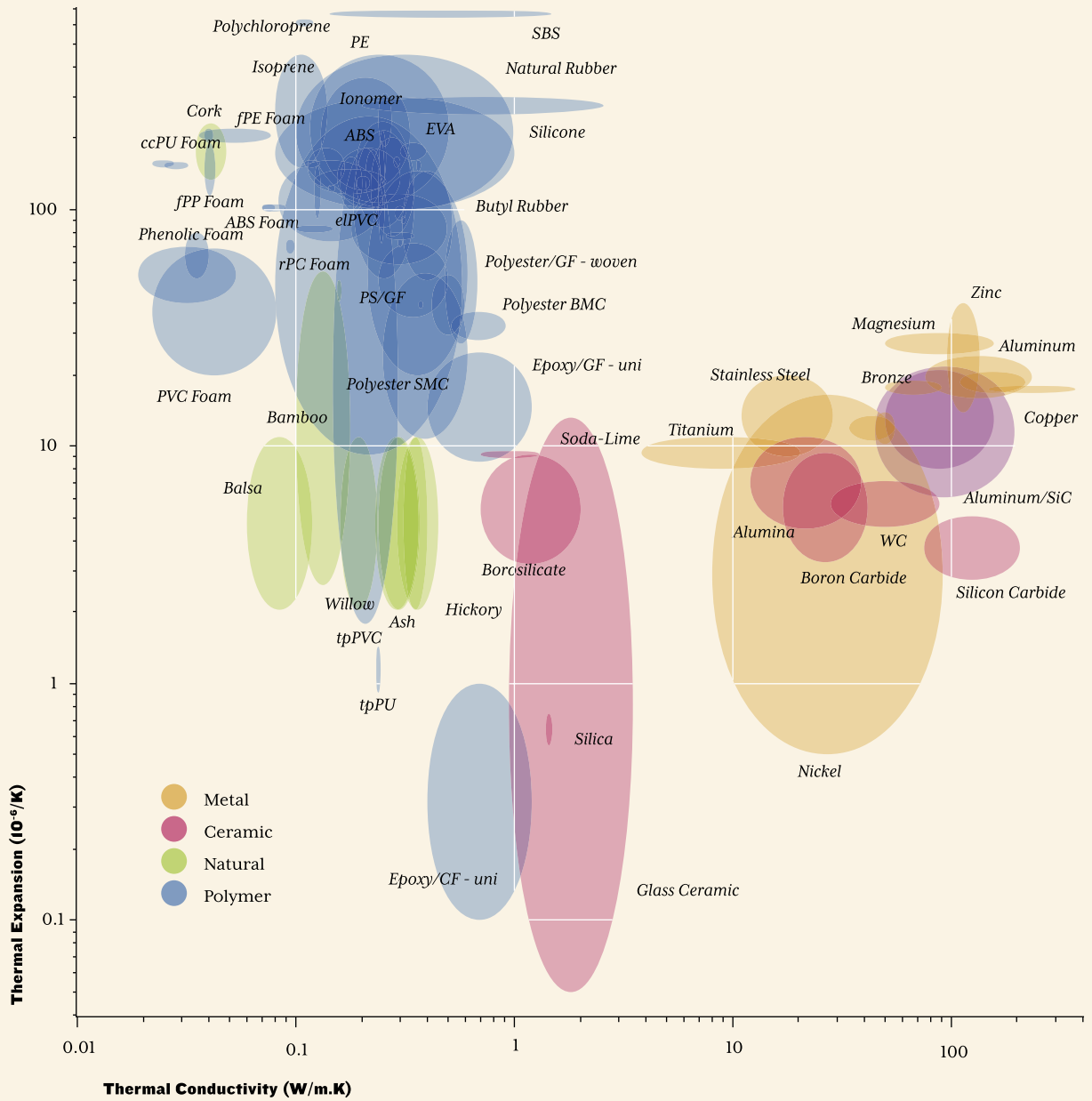
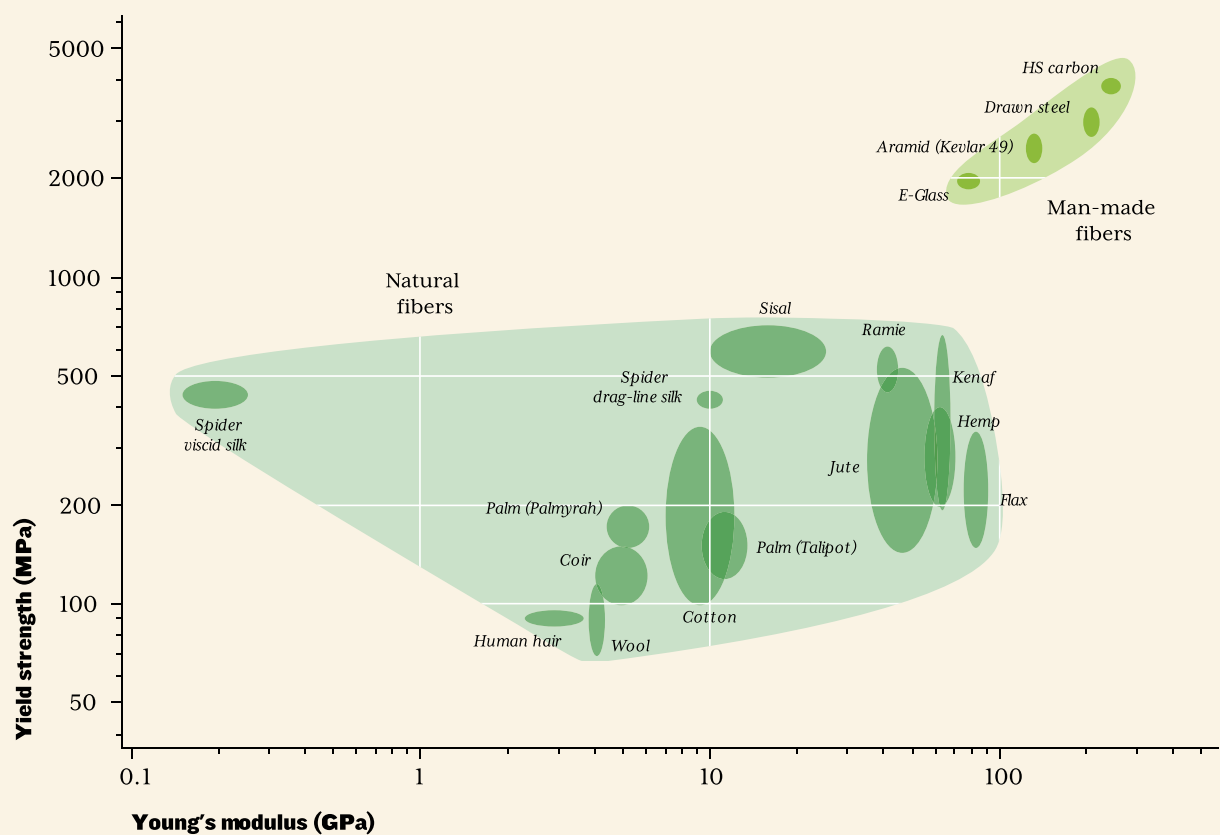


Chart 7 – Strength and Stiffness of Fibers

Fibers play a key role in design. They are matted into felt and paper, spun into thread and rope, and woven into cloth. Many have exceptionally high strength and stiffness, exploited in fiber-reinforced composites. Man-made fibers include glass, carbon, and Kevlar (aramid). Natural fibers, derived from plants and animals, include coir (from coconut husks), cotton, flax, hemp, jute, kenaf, ramie, sisal, and wool. This chart shows their tensile strength and modulus. Man-made fibers are stiffer and stronger than those of nature, but they are also heavier. When strength and stiffness per unit weight are important, natural fibers compete with those made by man.

Chart 7 – Strength and Stiffness of Fibers



Designations used in recycle marks (a) base polymers

E/P	ethylene-propylene plastic
EVAC	ethylene-vinyl-acetate plastic
MBS	methacrylate-butadiene-styrene plastic
ABS	acrylonitrile-butadiene-styrene plastic
ASA	acrylonitrile-styrene-acrylate plastic
C	cellulose polymers
COC	cycloolefin copolymer
EP	epoxide; epoxy resin or plastic
Imod	impact modifier
LCP	liquid-crystal polymer
MABS	methacrylate-acrylonitrile-Butadiene-styrene plastic
MF	melamine-formaldehyde resin
MPF	melamine-phenolic resin
PA11	homopolyamide (Nylon) based on 11-aminoundecanoic acid
PA12	homopolyamide (Nylon) based on -aminododecanoic acid or on laurolactam
PA12/MACMI	copolyamide(Nylon) based on PA12, 3, 3-Dimethyl-4, 4-diaminodicyclo-hexylmethane and isophthalic acid
PA46	homopolyamide (Nylon) based on tertramethylenediamine and adipic acid
PA6	homopolyamide (Nylon) based on – caprolactam
PA610	homopolyamide (Nylon) based on hexamethylenediamine and sebacic acid
PA612	homopolyamide (Nylon) based on hexamethylenediamine and dodecane-diacid (1,10-Decandicarboxylic acid)
PA66	homopolyamide (Nylon) based on hexamethylenediamine and adipic acid
PA66/6T	copolyamide based on hexamethylenediamine, adipic acid, and terephthalic acid
PA666	copolyamide based on hexamethylenediamine, adipic acid, and -caprolactam
PA6I/6T	copolyamide based on isophthalic acid, adipic acid, and terephthalic
PA6T/66	copoylamide based on adipic acid, terephthalic acid, and hexamethylenediamine

Designations used in recycle marks (a) base polymers

PA6T/GI	copolyamide based on hexamethylenediamine, terephthalic acid, adipic acid, and isophthalic acid
PA6T/XT	copolyamide based on hexamethylenediamine, 2-methyl-penta-methylene diamine and terephthalic acid
PAEK	polyaryletherketon
PAIND/INDT	copolyamide based on i, 6-diamino-2, 2, 4-trimethylhexane, i, 6-diamino-2, 4, 4-trimethylhexane, and terephthalic acid
PAMACM12	homopolyamide based on 3,3'-dimethyl -4,4'-diaminodicyclohexyl-methane and x acid
PAMXD6	homopolyamide based on m-xylylenediamine and adipic acid
PBT	poly(butylene terephthalate)
PC	polycarbonate
PCCE	poly(cyclohexylene dimethylene terephthalate)
PCTA	poly(cyclohexylene dimethylene terephthalate), acid
PCTG	poly(cyclohexylene dimethylene terephthalate), glycol
PE	polyethylene
PEI	polyetherimide
PEN	poly(ethylene naphthalate)
PES	polyethersulfone
PET	poly(ethylene terephthalate)
PETG	poly(ethylene terephthalate), glycol
PF	phenol-formaldehyde resin
PI	polyimide
PK	polyketone
PMMA	poly(methyl methacrylate)
PMMI	polymethylmethacrylimide
POM	polyoxymethylene, polyacetale, polyformaldehyde
PP	polypropylene
PPE	poly(phenylene ether)
PPS	poly(phenylene sulfide)
PPSU	poly(phenylene sulfone)

Designations used in recycle marks (a) base polymers

PS	polystyrene
PS-SY	polystyrene, syndiotactic
PSU	polysulfone
PTFE	polytetrafluoroethylene
PUR	polyurethane
PVC	poly(vinyl chloride)
PVDF	poly(vinylidene fluoride)
SAN	styrene-acrylonitrile plastic
SB	styrene-butadiene plastic
SMAH	styrene-malefic anhydride plastic
TEEE	thermoplastic ester- and ether-elastomers
TPA	polyamide thermoplastic elastomer
TPC	copolyester thermoplastic elastomer
TPO	olefinic thermoplastic elastomer
TPS	styrenic thermoplastic elastomer
TPU	urethane thermoplastic elastomer
TPV	thermoplastic rubber vulcanizate
TPZ	unclassified thermoplastic elastomer
UP	unsaturated polyester

Designations used in recycle marks (b) fillers

CF	carbon fiber
CD	carbon fines, powder
GF	glass fiber
GB	glass beads, spheres, balls
GD	glass fines, powder
GX	glass not specified
K	calcium carbonate
MeF	metal fiber
MeD	metal fines, powder
MiF	mineral fiber
MiD	mineral fines, powder
NF	natural organic fiber
P	mica
Q	silica
RF	aramid fiber
T	talcum
X	not specified
Z	others not included in this list

Appendix: Modeling Aesthetic Attributes

Softness (to the Touch)

Hardness is resistance to indentation and scratching. It is directly related to the material property of hardness H . Softness has to do with stiffness – or, rather, to lack of stiffness. The stiffness of a material in a given shape is proportional to its modulus E , another material property. It is convenient to have a single measure that allows materials to be ranked along a single axis. One that works here is the measure

$$S = EH$$

If s is small, the material feels soft; as s increases it feels harder.

Warmth (to the Touch)

A material feels “cold” to touch if it conducts heat away from the finger quickly; it is “warm” if it does not. Heat flows from the finger into the surface such that, after time t , a depth x of material has been warmed significantly while its remoter part has not. Transient heat-flow problems of this class all have solutions with the feature that

$$x = \sqrt{at}$$

where a is the thermal diffusivity of the material

$$a \approx \frac{\lambda}{\rho c_p}$$

here, λ is the thermal conductivity, c_p is the specific heat, and ρ is the density. The quantity of heat that has left each unit area of finger in time t is

$$Q = x\rho c_p = \sqrt{\rho\lambda c_p} \cdot \sqrt{t}$$

If Q is small the material feels warm; if large, it feels cold. Thus $\sqrt{\rho\lambda c_p}$ is a measure of the “coldness” of the material. Softness and Warmth are used as the axes of 4.22.

Pitch (of Sound)

Sound frequency (pitch) when an object is struck relates to the modulus, E , and density, ρ , of the material of which it is made. We use the quantity

$$P = \sqrt{E/\rho}$$

as a relative measure of natural vibration frequency, and thus pitch. If P is small the material's pitch is low; as P increases the material's pitch becomes higher.

Brightness (of Sound)

Sound attenuation (damping or muffling) in a material depends on its loss coefficient, η . We use the quantity

$$L = \frac{1}{\eta}$$

as a measure for ranking materials by acoustic brightness. If L is small the material sounds muffled; as L increases the material rings more. Pitch and Brightness are used as axes of 4.24.

Abrasion Resistant

Resistance to abrasion depends on many properties, but one – hardness, H – is of particular importance. One material is scratched by another that is harder, and it, in turn, can scratch those that are less hard. So we use hardness H as a relative measure of abrasion resistance.

Stiffness

Stiffness, for a given shape, is directly related to the material property “modulus,” E .

Resilience

Resilience is the ability to accept large deflection without damage. Deflection is limited either by yield (permanent deformation) or by fracture, that is, by the more limiting of the two quantities

$$\frac{\sigma_y}{E} \text{ and } \frac{K_{IC}}{E}$$

where σ_y is the yield strength and K_{IC} is the fracture toughness. We use the quantity

$$R = \frac{\sqrt{\sigma_y K_{IC}}}{E}$$

as a measure of resilience. Resilience and Stiffness are used as the axes of 4.29.

1. *The method is developed fully, with many examples, in the companion volume (Ashby 2005).*

Appendix: Selection by Analysis

We here paraphrase the analytical approach to materials selection. We give only the briefest outline.¹

Function, Objectives, Constraints, and Control Variables

Any engineering component has one or more functions: to support load, to contain a pressure, to transmit heat, and so forth. In designing the component, the designer has an objective: to make it as cheap as possible, perhaps, or as light, or as safe, or some combination of these. This must be achieved subject to constraints: that certain dimensions are fixed, that the component must carry a given load or pressure without failure, that it can function safely in a certain range of temperature, and in a given environment, and many more. Function, objectives, and constraints (7A.1) define the boundary conditions for selecting a material and – in the case of load-bearing components – a shape for its cross-section.

The performance of the component, measured by performance metrics, P , depends on control variables. The control variables include the dimensions of the component, the mechanical, thermal, and electrical loads it must carry, and the properties of the material from which it is made. Performance is described in terms of the control variables by one or more objective functions. An objective function is an equation describing a performance metric, P , expressed such that performance is inversely related to its value, requiring that a minimum be sought for P . Thus,

$$P = f[(\text{Loads}, F), (\text{Geometry}, G), (\text{Material}, M)]$$

or

$$P = f[F, G, M]$$

where “ f ” means “a function of.” Optimum design is the selection of the material and geometry which minimize a given performance metric, P . Multi-objective optimization is a procedure for simultaneously optimizing several interdependent performance metrics, P, Q, R .

This, in the abstract, sounds horribly obscure. A simple example will demystify the method. Consider the selection problem mentioned in the text: that of materials for the spoke of a racing bicycle wheel. The design requirements specify its length, L , and the load, F , it must carry. The *function* is that of a tie; the *objective* is to minimize the mass; the *constraints* are the specified load, F , the length, L and the requirement that the load be carried without failure. The *free variables* (those that, so far, are

7A.1: Details of Analysis

Function

What does a component do?

Objective

What is it to be maximized or minimized?

Constraints

What non-negotiable conditions must be met?

Free Variables

Which control variables are we free to adjust?

unspecified) are the cross-sectional area, A and the choice of material. The inputs to the model, which we now describe, are summarized in 7A.2.

The measure of performance is the mass, m – it is this that we wish to minimize. The performance equation describes this objective:

$$m = AL\rho$$

where ρ is the density of the material of which the rod is made. The length L is given but the section A is free; reducing it reduces the mass. But if it is reduced too far it will no longer carry the load F and this constrains the section, requiring that

$$\frac{F}{A} > \frac{\sigma_y}{S}$$

where σ_y is the yield strength of the material of the rod, and s is a safety factor. Using this to replace A in the equation for m gives

$$m > SFL \left[\frac{\rho}{\sigma_y} \right]$$

Everything here is specified except the term in the square brackets – and it depends only on the choice of material. The mass is minimized (and performance maximized) by choosing materials with the smallest value of ρ/σ_y , which is called a *material index*.

Material Indices

Each combination of function, objective, and constraint leads to a performance metric containing a group of material properties or material index; the index is characteristic of the combination. Table 7A.3 lists some of these; their derivation is detailed in the companion text. The point of interest here is that materials with extreme values of certain indices are well suited to meet certain sets of design requirements. The spoke is an example: materials with low values of ρ/σ_y are good choices. Indices allow comparisons. If the spoke is at present made from a reference material M_o and has a mass m_o , a competing material M_1 with mass m_1 will be lighter than M_o , for the same load-carrying capacity, by the factor

$$\frac{m_1}{m_o} = \frac{\rho_1/\sigma_{y1}}{\rho_o/\sigma_{yo}}$$

(where the subscript “o” refers to the reference and “1” to the new materials) giving a direct measure of the gain in performance achieved from switching from M_o to M_1 .

7A.2: Details of Analysis for a Bicycle Spoke

Function

Tie rod

Objective

Minimize mass

Constraints

Specified length L Specified load F , no failure

Free variables

Cross-section A Choice of material

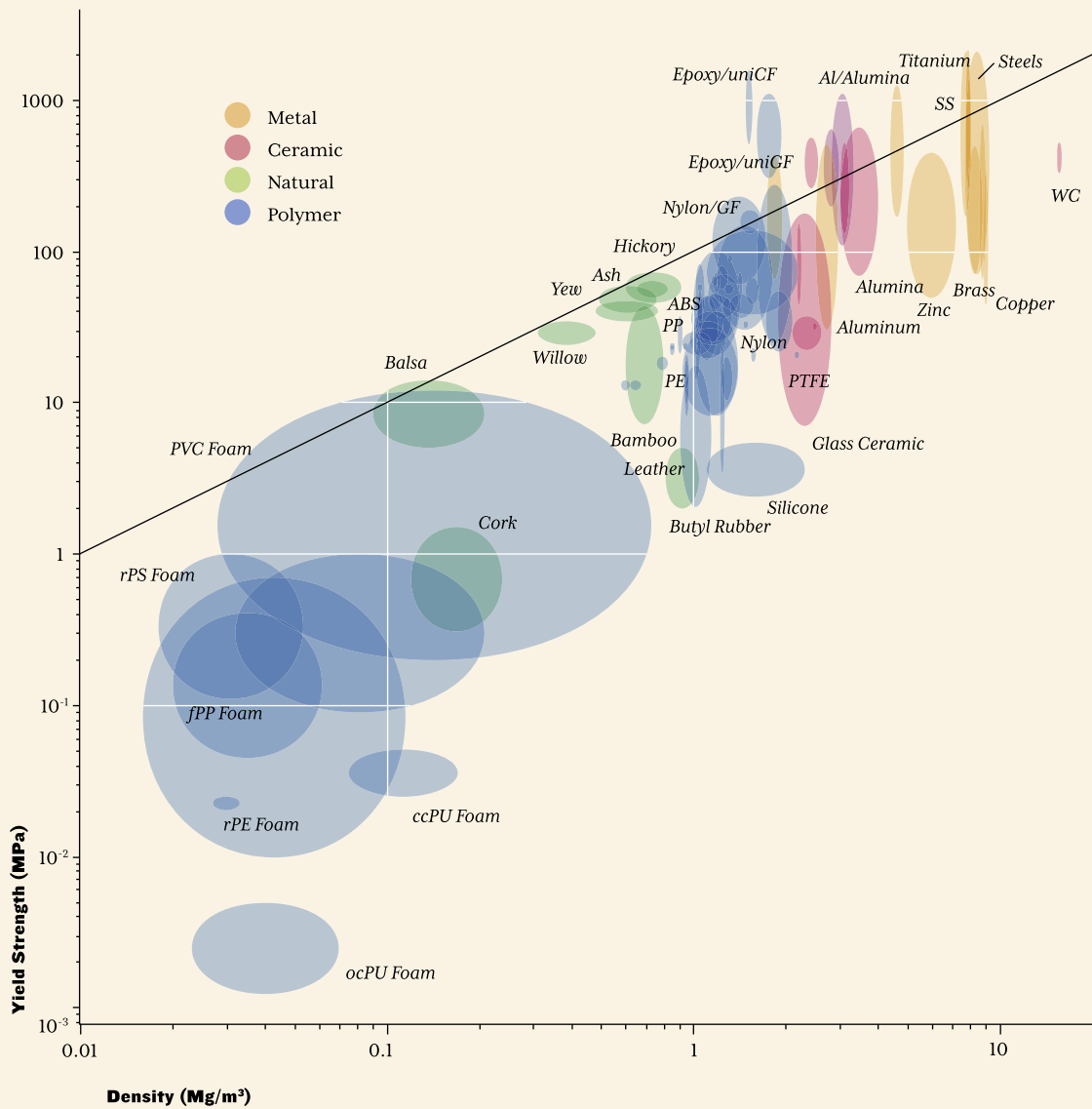
7A.3 Material Indices

When you want to optimize material choice to meet purely technical requirements, indices act as a guide.

Function, Objective and Constraint	Minimize index
Tie, minimum weight, stiffness prescribed (Cable support of a lightweight tensile structure)	ρ/E
Beam, minimum weight, stiffness prescribed (Aircraft wing spar, golf club shaft)	$\rho/E^{1/2}$
Beam, minimum weight, strength prescribed (Suspension arm of automobile)	$\rho/\sigma_y^{2/3}$
Panel, minimum weight, stiffness prescribed (Automobile door panel)	ρ/E^A
Panel, minimum weight, strength prescribed (Table top)	$\rho/\sigma_y^{1/2}$
Column, minimum weight, buckling load prescribed (Push-rod of aircraft hydraulic system)	$\rho/E^{1/2}$
Spring, minimum weight for given energy storage (Return springs in space applications)	$E\rho/\sigma_y^2$
Natural hinge, maximum distortion, flexure without failure (Inexpensive hinges)	E/σ_y

(ρ = density; e = Young's modulus; σ_y = elastic limit)

Software systems exist that allow selection of materials to meet technical constraints. The output of one of these is shown in 7A.4. The axes of this diagram are yield strength σ_y and density ρ ; each little bubble describes a material. The diagonal line isolates materials with low values of ρ/σ_y , the starting point for choosing materials for the spoke. To this can be added requirements of corrosion resistance, impact resistance, stiffness and so forth, narrowing the choice. One more step is necessary: some of the candidates in 7A.4 are more expensive than others. How can weight be balanced against cost?



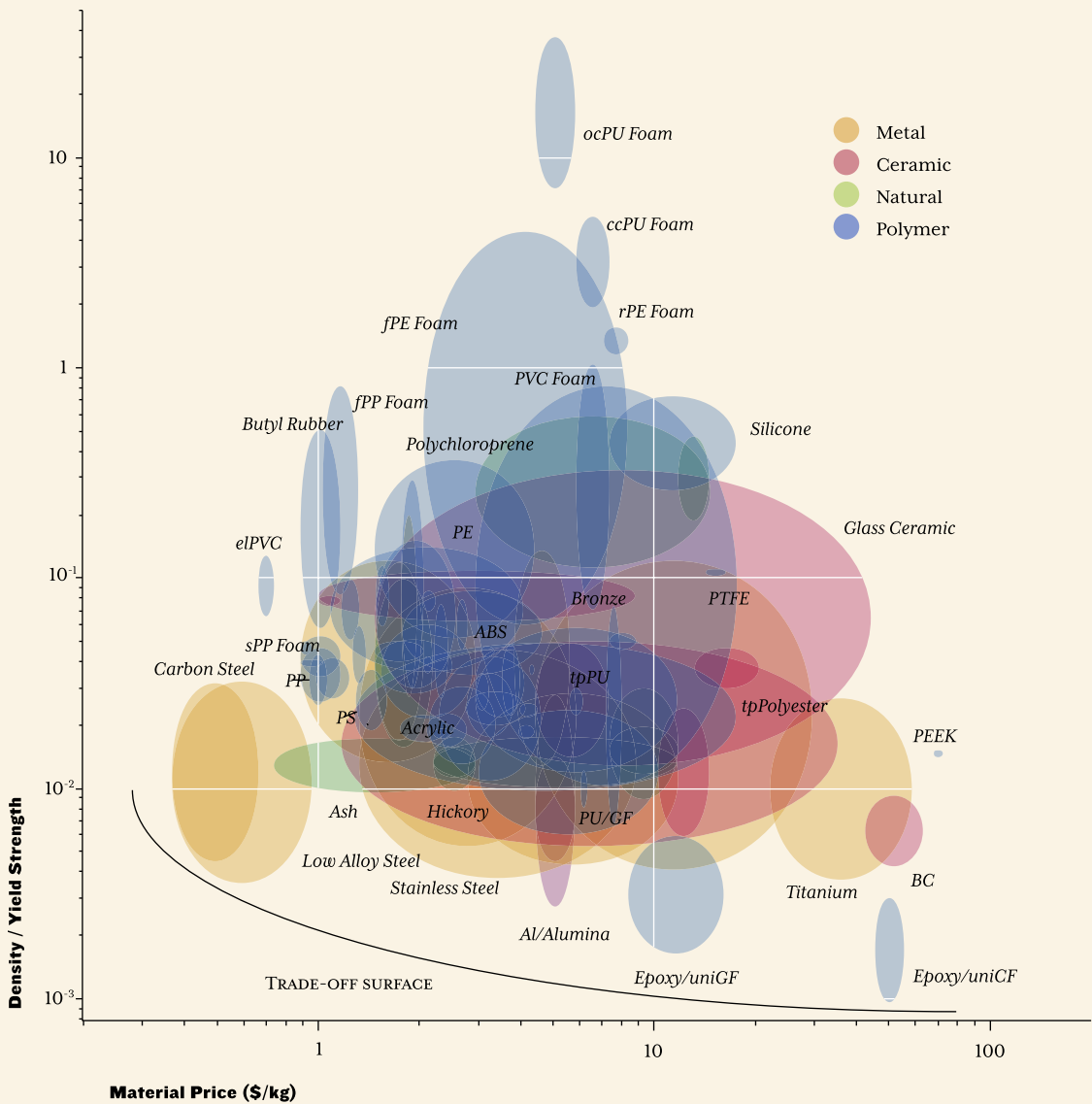
7A.4 Optimizing Selection

A strength-density chart.

Materials with low values of ρ/σ_y lie above the diagonal line, at the top left (CES Edu, 2009).

Multi-Objective Optimization

Greater discrimination is possible by plotting trade-off diagrams of which 7A.5 is a simple example. Here the material group ρ/σ_y is plotted on the vertical axis, and material cost/kg on the horizontal one. The plot allows materials to be compared on the basis both of performance and of cost. The most attractive candidates lie on or near the trade-off surface (solid line); these offer both low mass and low cost. It shows that carbon steels, low alloy steels, aluminum alloys, and stainless steels are all good choices. Carbon fiber-reinforced polymers (CFRP) offer a lower mass than these, but at a considerable increase in material cost. Titanium alloys are also more expensive, and have greater mass – they are not a good choice.



7A.5 Trade-Off Analysis

Here a compromise is sought between minimizing weight and cost. The materials at or near the trade-off surface are the candidates; the final decision depends on how much each attribute is valued (CES Edu, 2009).

Exercises

Here are some things to try. Most can be done individually, some require a group. Some need a supply of materials. The list is organized to match the content from each chapter.

Chapter 1. Introduction

Materials in the Real World. Examine the use, in products and structures, of one material class from the following list:

Woods	Glass	Metals
Ceramics	Polymers	Textiles

Seek examples of their use by visiting shops, observing products and structures in the street, stations, and museums. Prepare a commentary, with sketches rather than photographs, bringing out the way the material has been used, the forms that it has allowed, and the associations and perceptions its use has created.

Materials and Brand. Find three products that, by their materials and brand, are instantly recognizable.

Chapter 2. What Influences Product Design?

Product Forensics. Dissect a product of your choice, examining how materials have been used, doing your best to identify the material, and the way it was processed. Examine how the design choices used for the interior of the product have influenced its external form. How far does the external form express the function of the product?

Associations. Analyze the responses of these questions (assuming that responses are available from – say – 10 participants): What does this product remind you of? What meaning does it have? Do you associate it with any person, story, experience in particular?

1. Examine the responses, judging the degree to which participants agree on associations.
2. Use statistical methods to identify association-choices with a significant degree of common meaning.
3. Use cluster analysis to group materials with similar associations.

Types of Innovation. We already reviewed the design of a USB key within one specific context of a framework for innovation. Re-examine the other products in the same framework.

Product Icons. Many very simple products have had (and continue to have) very long lives – they become a classic, an icon. Research the history of one of these products, seeking the context (Who, What, Where, When, Why) the inventor had in mind, and the present-day view of their utility, aesthetics, and associations. Can you identify what has made its design so durable, sustainable, long-lasting, classic, iconic?

Product Stories. Select and examine a product and ask: What does the product do? Who will use it? Where? When? Why? Describe the aesthetics of the product. What are its associations? How did the designer create them? Why? What is your perception of the product? What made you feel that way? How (intentionally or unintentionally) did the designer create that perception? And finally: What was the designer trying to say?

Value and Price. (A) Today – 2012 – bagless vacuum cleaners vary in price by almost a factor of 10 (an Argos VC 403 is priced at £38 (\$53), a Dyson DC23 is priced at £333 (\$466). There is a market for both, so a market sector must exist that perceives the value of the more expensive cleaner to be greater than its high price. How has Dyson created this perception of value? Examine these (or two equivalent) products on the Internet and analyze how he has done it.



Argos VC 403 Bagless Cleaner



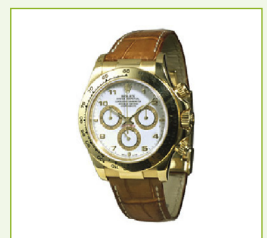
Dyson DC23 bagless cleaner

(B) Carry out a comparison and analysis like that of the previous exercise for suitcases (luggage) and refrigerators. What, for a given suitcase or refrigerator capacity, is the range of price? What aspect of product character gives the most expensive of the products its high value? The prices, sizes, and other information you need are readily available in Consumer Magazines such as Which? or in product-comparison websites.

(C) Watches vary in price by a factor of over 10,000. I have a very cheap watch which I like because it has a stop-watch and is waterproof, so can swim with it. It is extremely accurate and if I lose it a new one will cost me £5.80 (about \$9) from Amazon. You see it on the left, below. The other watch is a Rolex, currently priced at \$11,870 but that is nothing compared with the Sky Moon Tourbillon 5002 P from Patek Philippe which will set you back \$1.5 million. How do the makers of really expensive watches create the value that their products apparently have, at least to some people? Their advertisements in glossy magazines and their websites give away a lot. Research these to reveal how materials, associations, brand-image status can create value.



Casio watch, Price about \$9



Rolex Dayton Price \$11,870

Humor. (A) Paperclips (invented 1899) are one of the simplest of products with one of the longest lives. Every office has them. They don't normally arouse interest or amusement. Here is an example of a re-design that provides these missing elements. Find a really simple everyday-product (perhaps one from the table in the previous



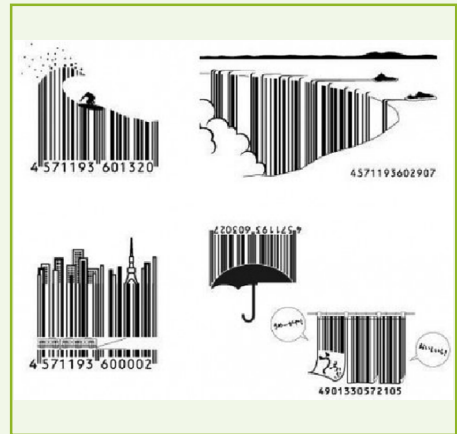
A paperclip



Variations on the theme of paperclips

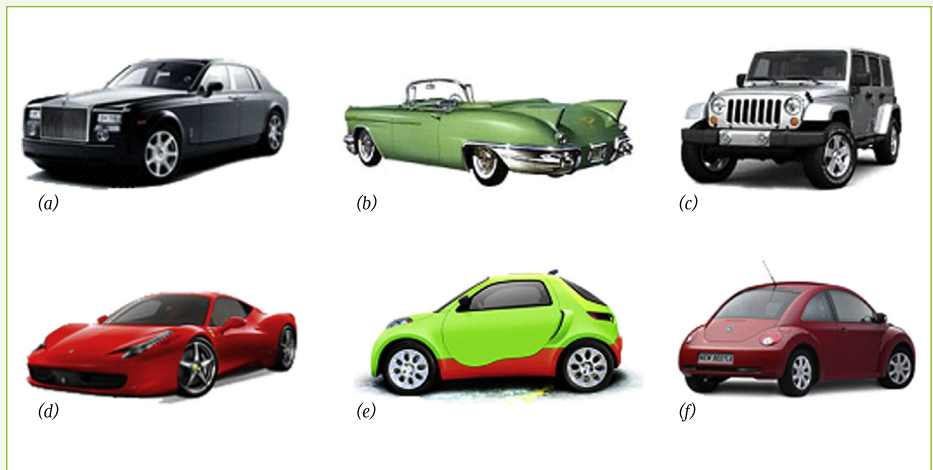
exercise) and re-design it to introduce an element of humor.

(B) Bar codes now appear on almost every product for purposes of identification and stock control. They are so dull that they become almost invisible – just as muddy blemish on the back or bottom of the product. But they don't have to be dull – a little imagination can make them objects of delight. Re-design the bar code of a chemistry textbook and packaging for plant food in order to give them a sense of humor.



Various bar codes

Associations. Write down the first association that comes to your mind when you glance at each of the images of cars shown below. How has the designer suggested this association?



Perceptions. Look at the six car-images again and ponder on them for a moment. How do you perceive each one? How do they make you feel? If you had a choice of any one of these, which would you choose? Why?

Product Evolution. Explore the evolution of a product, documenting its design history (examples were given in Chapter 3). Report on the ways in which the choices of material, processing, and surface treatment have been used to meet technical and

aesthetic requirements and to create associations and perceptions. Start with your own observations, then seek information from design-history books and contemporary magazines and catalogs. Products that are well documented in this way include

Radios	Bicycles	Pens
Vacuum cleaners	Mobile phones	Cars
Skis	Personal computers	Something else...?

Chapter 3. Materiality, Design, and Creativity

Visual Storytelling. Identify a product and the environment in which it will be used. Assemble images, samples, sketches, and other concept-suggesting material and assemble them into a mood board.

Material Metaphors. An “iron” is used for smoothing crumpled clothing. It derives its name from the material of which it is made. A “glass,” similarly, is a product that shares its name with its material. What – if you could design it, would be made of...

Aluminum?	Polyethylene?	Zinc?
Polycarbonate?	Nickel?	Nylon?
Bamboo?	Copper?	

Associations of Materials. What do you think of when you see something made of gold? You might – because of its expense – associate it with wealth and luxury; or perhaps – because it is a visible symbol of riches – with extravagance and power; or perhaps – because of its total resistance to chemical attack – with stability and permanence. What associations would you attach to the following materials? Ask: “What do you think of when you see something made of...?”

Machined steel	Lead	Polished cherry wood
Stainless steel	Polyethylene	Plastic with a wood surface
Rusted steel	Nylon	Marble
Brushed aluminum	Diamond	Glass

The 9-window Method. The 9-window method for inspiring new thinking is illustrated in the Text and in Appendix 2 of the White Paper referred to on page 1 of these exercises. The product to be re-designed is placed in the middle box of a 3×3 matrix. Filling in the other 8 boxes expands thinking on both the temporal and special scales. Choose a contemporary product and construct a 9-window analysis of how it might be developed further, using the “Super-system” level to create the context and explore the “Sub-system” level by researching new technologies that could provide the necessary functionality.

Chapter 4. Materials – The Stuff That Surrounds Us

Chromatic Series. Develop a chromatic series of materials, as Itten suggested to his students in the Bauhaus course. The most recognizable chromatic series is that of color: red, orange, yellow, green, blue, violet. This series provides a limited structure and a visual representation of a wide spectrum of colors. The same is needed to guide designers across the wide range of available materials.

The Internet is Green. With a focus on sustainability, do secondary research (on the internet) for any or all of the following for a selected material and/or manufacturing process and/or product category:

1. Environmental legislation as it impacts material choice.
2. Software tools to help in conforming with the EUP Directive, the reach directive, and the WEEE directive.
3. Carbon trading schemes, and their successes and failures.

Usability. Identify a product that, in your experience, is difficult to use. Are the difficulties physical (controls that are hard to reach or use), failure to communicate (unintelligible controls or responses), or environmentally disturbing (too noisy, too hot). How could the product be improved without losing the character that the designer sought to create?



L'Express coffee maker

Exploring Context. (A) Bikes come in many forms, each aimed at a particular sector of the market – sprint bikes, touring bikes, mountain bikes, shopping bikes, children's bikes, folding bikes. Use your judgment to write a “context” statement for each of these by answering the following questions (Who were these products designed for? What were they made of and how? Where were they designed? When and why were they designed?).

(B) The images (left) show two contrasting coffee machines. Analyze the context for which these were designed by responding to the five questions: Who? What? Where? When? Why?

(C) Pick a product. Make a poster suggesting the Who, What, Why, Where, When of its context.



Lacimbale coffee machine

Chapter 5. Manufacturing; Shaping, Joining, Surfaces

Materials and Manufacturing: Search for five product examples that show expression through materials, shaping, joining, surfaces, and manufacturing, in general.

Chapter 6. Form Follows Material

Inspired by Materials. Sketch designs for one product as it would appear if made from each of several given materials. For example, design a desk made of metal, of a polymer, of glass, and of wood.

Material Exploration. Brainstorm on the uses to which a common material, or one that is new or unusual (if available), could be put. Both functional and aesthetic solutions are possible. Take one of the ideas emerging from the brainstorm and develop it further, trying out the material in the chosen role. Describe the features of the idea and how the material contributes to these features. (The project requires materials samples and is best done with a group of individuals attempting the same result.)

Chapter 7. Material Selection

Product Re-Design. Dissect a product, identifying the function both of the systems it contains and of the individual component. Explore alternatives – how could one or more functions be achieved in other ways? Could components be re-designed using other materials? What changes would these alterations allow in the number of parts in the product and in the design of its external form?

Building Associations. You are asked to design a rack for holding CDs in a den, study, or home, using the choice of material to prompt associations in the mind of the purchaser or user. What materials (colors, finishes, styles) would you choose to suggest that the rack is...

State of the art, technically advanced	Desirable to children
Environmentally friendly	Durable, robust
Easy to use, non-threatening	Fast, streamlined, aerodynamic

Chapter 8. Materials and Sustainability

Identifying Polymers. A product contains components with the recycle marks TPA and PMMI-CF-30. What are they? Answer: Reference to the Appendix identifies the first as polyamide thermoplastic elastomer and the second as polymethylmethacrylimide with 30% carbon fiber.

Tagging Shreds. Many products are shredded at end of life. If the shredded material is to be recycled, the shredded fragments must be sorted. Techniques based on density, magnetic and electrical signatures allow the primary sorting of metals but polymers all have about the same density, are non-magnetic, and almost all are insulators. Thus there is need for an internal identifier for polymers that can survive

both product life and subsequent shredding to identify every shredded chip. How might this be achieved? Answer. Tagging polymers to survive shredding requires that embedded tags are distributed within the material. A low concentration of submicron or nanoscale magnetic particles could provide the marker; and their concentration, externally measured, could code information about composition. Alternatively, distributing particles that fluoresce or absorb light in the UV range at low concentration could carry composition data via color spectrum.

Bio-polymers – Our Future? Bio-polymer production is now half a million tonnes per year. This sounds a lot, but is it? Compare this figure with the annual production of polyethylene (a quick search on the Internet will give the value) – polyethylene is just one of a family of commodity polymers. What is the ratio?

Bio-polymers – Some Constraints. Suppose that half of today's production of polyethylene were to be replaced with an equal tonnage of bio-polymers, what land area would be required to provide the feedstock, assuming this requires $5 \text{ m}^2/\text{kg}$ of bio-polymer per year?

Production Volume. Bio-polymer production is now half a million tonnes per year and is growing at $r = 22\%$ per year. The production of a commodity growing at $r\%$ per year doubles in $70/r$. How long will it take the production of bio-polymers to double? Half a million tonnes of bio-polymer per year sounds a lot. But is it? Compare this figure with the annual production of polyethylene, easily found by quick web search. What is the ratio? (Polyethylene is just one of the four large-volume commodity polymers: PE, PP, PVC, and PET). Suppose that today's production of polyethylene were to be replaced with bio-polymers, what land area would be required to provide the feedstock, assuming this requires $5 \text{ m}^2/\text{kg}$ per year? How does this compare with the land area of the Netherlands ($41,526 \text{ km}^2$) of Massachusetts ($27,336 \text{ km}^2$)? Answer. The area needed is $40,000 \text{ km}^2$, roughly the entire land areas of the Netherlands, or almost twice the land area of Massachusetts.

Green Materials. What, to your mind, are the associations of bio-polymers? (What do they suggest to you?) How do you perceive them? (Desirable – Undesirable? A good idea – A bad idea? Green: derived from nature – Ungreen – absorbing fertile arable land, water, and fertilizers?) Why to you perceive them in the way you do?

Bio-polymer Marketing. Here is a little design exercise. You have acquired the rights to market a new bio-polymer – one made from a fast-growing, prolific, crop. What are you going to call it? Apply the design method: Gap? Define problem (what?). Explore alternatives (how?). Select solution (which?). Here is a challenge: Create a name for a new bio-polymer.

- What? An evocative name.
- Why? To convey that it is bio, green.
- Why? To sell it to an increasingly eco-concerned public.
- How? Some synthesis of green words or notions? Green. Renewable. Responsible. Benevolent. Saving the future. Cool. Next generation. OK, then, here are some tries: Respoxy, Biofutene Gen4biocool, Benegen.
- Which? Respoxy (definite no). Biofutene (I don't think so – too obvious), Gen4biocool (kind of nice but too many syllables). Benegen (maybe – might have to go with that).

Here are some real names at present used for grades of bio-polymers. Bio-Flex, Biopearls, Bioplast, Ceramis, Compostable, Earthfirst, Ecopond, Ecovio, Evlon, EnviRo, Fibrolon, Ingeo. Rank them by their imagination and clarity.

End-of-Life Options. Many products are thrown away and enter the waste stream even though they still work. Can imaginative design of products or systems or both reduce this waste? Search the Internet for examples that appeal to you. What options are available for coping with the waste stream generated by modern industrial society?

Material ReUse. Car tires create a major waste problem. Use the Internet to research ways in which the materials contained in car tires can be used, either in the form of the tire or in some decomposition of it.

Packaging. List three important functions of packaging. Then – as a member of a design team you are asked to devise ways of reusing polystyrene foam packaging – the sort that encases TV sets, computers, appliances, and much else when transported – most of which at present is sent to landfill. Use free thinking: no suggestion is too ridiculous.

Recycling Codes. You are employed to recycle German washing machines, separating the materials for recycling. You encounter components with the following recycle marks: “5,” “PA6-GF10,” “PP-T20,” “PS-GD15” ... How do you interpret them? Answer. The Appendix to Chapter 8 gives the information needed to crack the codes. (a) Polypropylene. (b) Polyamide 6 (Nylon 6) with 10% glass fiber. (c) Polypropylene with 20% talc. (d) Polystyrene with 15% glass fines (powdered glass).

Chapter 9. New Materials

Finding Applications. New materials often appear to have exciting properties (and are promoted in that light by their developers) yet it can be surprisingly difficult to find applications for them. Examples of new materials are metal foams, lattice

structures, shape-memory alloys, and bio-polymers. Set up a discussion group to seek new applications for one of these:

- First ask yourself: what is interesting, visually and functionally, about the material?
- What does it cost now? What might it cost if mass produced? Which industrial sector (Products/Auto/Architecture...) might be most interested in using it? Why?
- Arrange a brain-storming session with a group of industrial designers from that sector. Let them handle the material in as many different forms/colors/textures as it is available. Give a brief presentation of the properties and processing of the material. Let the imagination of the designers do the rest.

What's in a Name? Here are some real names at present used for grades of bio-polymers. Bio-Flex, Biopearls, Bioplast, Ceramis, Earthfirst, Ecopond, Ecovio, Evlon, EnviRo, Fibrolon, Ingeo. Identify the polymer described by each and then rank them by their imagination and clarity.

Chapter 10. Conclusions

Project 1 – Product Deconstruction

For this assignment, first select an object as a team that you would like to deconstruct. You will need duplicates (2).

First, take it apart! Deconstruct the object you selected so that you have a clear understanding of how it was made, what it's made of, and why. Work slowly and carefully making sure to take apart the product as much as possible in the reverse order of how it was put together and keep each individual component in its original shape. Evaluate how each component is an ingredient in the final experience of the product. Tell a story from the inside-out!

Second, slice it! Deconstruct the same object in a way that is extremely clean and precise: "cut-it-in-half." Of course you may not be able to exactly bisect it, but please remember you are attempting to show the beauty of the object and its story from the inside-out. In some cases, it may be more useful to section in some other location (not the mid-point), decide as a group what works best for you but please focus on the aesthetics and form of the final part. Make it beautiful.

Plan to spend 5–10 minutes sharing your deconstruction. Please take good pictures (use a macro lens if possible) and share them as part of your presentation. Bring the physical object as part of your presentation. Be prepared to tell us why you picked this object for your surgery. Show us what you found. Tell us what you learned and what questions you have as a result. Write a brief essay (one paragraph) describing what you sectioned, what you found inside of it, and what you learned. Sketches or photos would be admired. Please focus on the material and manufacturing details of how the product was made – both from an aesthetic as well as functional perspective.

Think about why the designer and/or company made decisions in material selection, manufacturing process selection, or final assembly. Have fun!

Project 2. Material Expression

The purpose of this assignment is to find inspiration and solutions in materials and manufacturing processes that are offered to designers. There is an expanding palette of materials to work with in design, and usually materials are seen as the solution to a problem because they can do something that nothing else can or they can do the same thing for less money. In this assignment, you are asked to design an object (not a product) that expresses the unique attributes of a material. Pick a material from this list, or pick your own material – focus on something that is simple and ordinary so you are forced to look at it differently: Aluminum, Polycarbonate, Stainless Steel, Birch, Silicone.

Consider your material in detail. Learn about everything that it's good at and everything that it's bad at. Consider its extreme characteristics and its behavior. When looking to understand the attributes of your selected material, look at existing products across many industries and talk directly to material suppliers or manufacturers, use reference texts and the Internet for more detailed information. Please document your research and creative process.

Use this new understanding of your material and its unique attributes to design, visualize, and build (if possible) an object that expresses one or more (but not many) unique attributes of the material. Feel free to include any of the following: text, photograph, sketches, line drawings, 2D or 3D renderings, material samples, solid CAD models, animated videos, physical prototypes, etc. The best assignments will be made real, within the constraints of your own skills (existing and learned) and within the constraints of your local prototyping or production facilities or vendors.

Project 3. Factory Storytelling

Start by discovering a manufacturing company to which you already have access or with whom you can develop a mutually enthusiastic, trusting relationship. If you have a personal contact in a manufacturing firm, that could be a wonderful resource. If you have a definite manufacturing process of interest, that would be another good way to select a site. If you are well connected with a non-local company, and can afford the travel, that would also be appropriate. Some of our field trip hosts may enjoy being the target of your investigations.

Your research site might be associated with agriculture, aerospace, consumer electronics, job shop services, soft goods, environmental products or operations, medical devices, etc. That is to say, we will enjoy learning about a broad diversity of kinds of manufacturing. Tell the story of a manufacturing operation from the inside-out. Teach us something new about this manufacturing process and/or factory. Make your presentation highly entertaining.

Please pay attention to any combination of three aspects of the organization whose story you tell: (1) the technical aspects of manufacturing processes (material transformation), (2) the business aspects of the organization you visit (manufacturing systems and the business of making), and (3) a human-centered story of the organization. You need to do include all three of these parts of the story, but the amount of focus on each one may vary depending on where you visit and what your team is excited about. Focus on telling a good story!

Additional Exercises (Using the CES EduPack and Selector Software)

CES Project Files for the maps of aesthetic properties (warmth, softness, etc.) are available from the Granta Design Teaching Resources website. They recreate CES versions of the property charts shown in the text of this book (using the latest Granta data) and allow the user to manipulate them, add new materials, and select materials that have particular values of the axis-variables and print datasheets for them.

Exploration and Browsing. Open each of the Project Files mentioned above and explore them. Click on bubbles that at present have no labels to bring up their material name. Double click on the material name to bring up its data sheet.

Material Search. (A) Open the Price – Transparency Project. Find, on the chart, the most transparent polymers (the ones that are optically clear). Print out a record for the cheapest one. (B) Bells, gongs, and alarms require materials with minimum acoustic damping – that means high acoustic brightness. Open the Acoustic brightness – Pitch Project. Find, the three with the greatest acoustic brightness. Print out a record for the one with the brightest. (C) Open the Cool-Warm Soft-Hard Project. Use the Change button to bring up the other databases available in the system you have got – one is CES EduPack Level 3. Click on this, and click YES to the question about applying it to the present project. The axes of the plot are retained, but the roughly 100 materials on the original chart are replaced by about 3000. Which is now the coldest to touch?

Material Selection. Open the Cool-Warm Soft-Hard Project. Use the BOX selection tool to find materials that are the coldest and the warmest to touch.

A Practical Reference for Inspiration

Products are made from materials, using manufacturing processes. There are many materials and processes, but a small subset account for most specifications in product design. This reference assembles profiles for materials and manufacturing; portraits for the designer, so to speak. The profiles, and the information they contain, can be retrieved by using the conventional index at the end of the book or by the hierarchical tree included in the introduction to each set of profiles.

The material profiles start on page 174; those for manufacturing on page 236. Commonly used materials and manufacturing processes get a full-page profile; less common ones are grouped together and profiled more briefly.



Material Profiles

Materials are the stuff of design, and throughout history have dictated its opportunities and its limits. The ages in which man has lived are named for the materials he used: stone, bronze, iron, plastics, and – today – silicon. But today is not the age of just one material; it is the age of an immense range of materials and the combinations these allow. And people (your customers) are more aware of issues related to material selection due to the emergence of the idea of sustainability. There has never been an era in which the evolution of materials was faster and the sweep of their properties more varied. The menu of materials has expanded so rapidly that designers can be forgiven for not knowing that half of them exist. Yet not-to-know is, for the designer to risk failure: innovative design is enabled by the imaginative exploitation of new or improved materials. There is no reason to expect that the pace of material development will slow so things can only get worse (or better!).

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The Evolution of Engineering Materials with Time

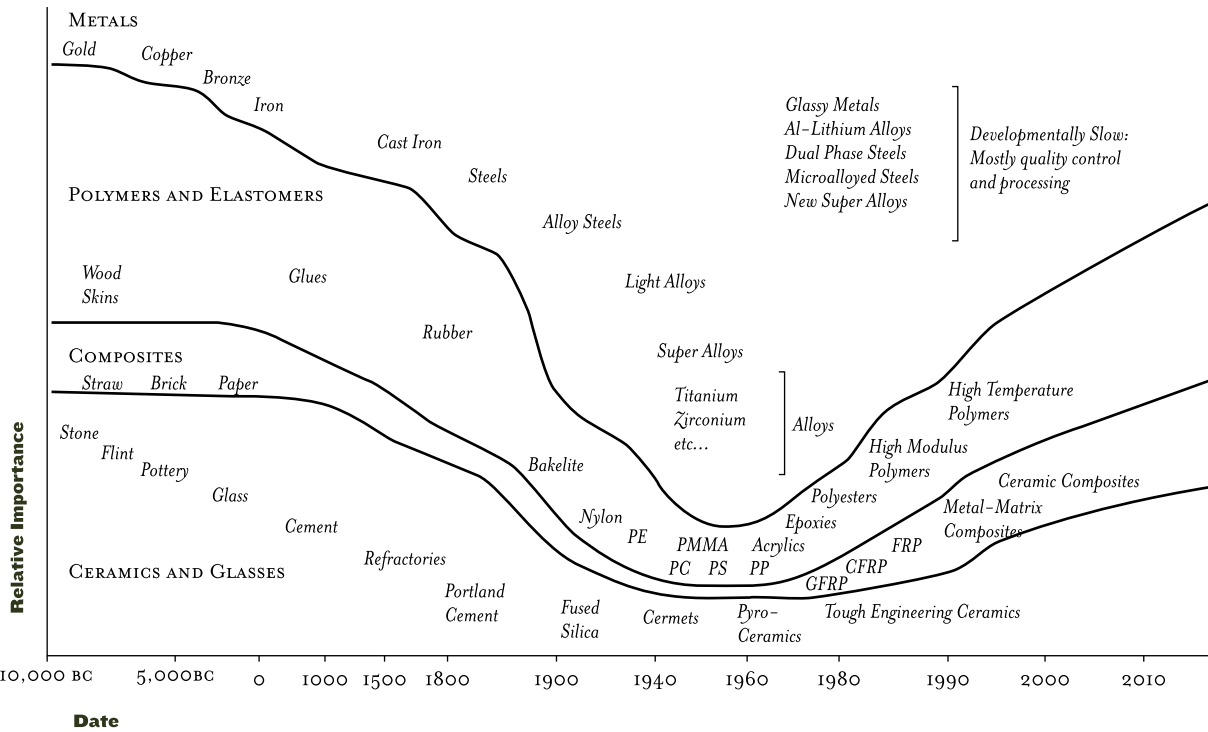
Relative importance in the Stone and Bronze Age is based on assessments of archeologists; that in 1960 on allocated teaching hours in UK and US universities; that in 2020 on prediction of material usage in automobiles by manufacturers.

Material Evolution

The figure at the bottom of this page illustrates the pattern and increasing pace of the evolution of materials. The materials of pre-history (>10,000 BC, the Stone Age) were ceramics and glasses, natural polymers, and composites. Weapons – always the peak of technology – were made of wood and flint; buildings and bridges of stone and wood, clothing of fur, and skin. Naturally occurring gold and silver were available locally but played only a minor role in technology. The discovery of copper and bronze and then iron (the Bronze Age, 3000 BC to 1000 BC, and the Iron Age, 1000 BC to 1620 AD) stimulated enormous advances, replacing the older wooden and stone weapons and tools. Cast iron technology (1620s) established the dominance of metals in engineering; and the development of steels (1850 onward), light alloys (1940s), and special alloys since then consolidated their position. By the 1960s, “engineering materials” meant “metals.”

There had, of course, been developments in the other classes of material: Portland cement, refractories, and fused silica among ceramics; synthetic rubber, Bakelite, and polyethylene among polymers; but their share of the total materials market was small. Since 1960 all that has changed. The rate of development of new metallic alloys is now slow; demand for steel and cast iron has in some countries actually fallen. Polymers have displaced metals in an increasing large number of markets, including those central to the metal-producing industry such as the automobile. The composite industry continues to grow strongly and projections of the growth of production of the new high performance ceramics suggest substantial expansion here also.

This rapid rate of change offers opportunities that the designer cannot afford to ignore. The following pages contain character sketches of the common polymer, metal, ceramic, composite, and natural materials, highlighting aspects of importance to design. Specific material profiles follow.



Polymers

Although nature's polymers – woods, wool, leather – are the oldest of the world's materials, the commodity polymers of today have little that is natural about them; they are the chemist's contribution to the materials world. Almost all are synthesized from oil (although they don't have to be) and are made from the simplest of atoms: carbon, hydrogen, oxygen, chlorine, and an occasional whiff of nitrogen or fluorine.

Thermoplastics

Thermoplastics soften when heated and harden again to their original state when cooled. This allows them to be molded to complex shapes. Most accept coloring agents and fillers, and many can be blended to give a wide range of physical, visual, and tactile effects. Their sensitivity to sunlight is decreased by adding UV filters, and their flammability is decreased by adding flame retardants. The common thermoplastics are listed in the adjacent table. They include polyolefins (polyethylene, polypropylene), PVCs, polystyrenes, acrylics, and certain polyesters (PET and PBT). Some are crystalline, some amorphous, some a mixture of both. The properties of thermoplastics can be controlled by chain length (measured by molecular weight), by degree of crystallinity, and by blending and plasticizing. As the molecular weight increases, the resin becomes stiffer, tougher, and more resistant to chemicals, but it is more difficult to mold to thin-wall sections. For thin-walls, choose a low molecular weight resin; for higher performance, choose one with higher molecular weight. Crystalline polymers tend to have better chemical resistance, greater stability at high temperature, and better creep resistance than those that are amorphous. For transparency the polymer must be amorphous; partial crystallinity gives translucency. The most transparent polymers are acrylics, PC, PS, and PET.

Some polymers crystallize faster than others: polyethylenes crystallize quickly but polyesters do so more slowly – they remain amorphous under normal cooling rates. Crystalline polymers have a more or less sharp melting point, which must be exceeded for molding. Amorphous polymers do not; instead they progressively soften and become more fluid as temperature increases above the glass transition temperature; they must be heated above this temperature for extrusion and injection molding. The processing force required to generate flow decreases slowly as temperature rises above the glass transition temperature. Amorphous polymers have greater impact strength and relatively low mold shrinkage. Semi-crystalline polymers have higher shrinkage because of the volume change on crystallization.

Holes and ribs reduce the effect of shrinkage in a thermoplastic part. Areas near the filling gate tend to shrink less than areas farther away. Shrinkage increases with wall thickness and decreases with higher molding pressures. Fiber-filled polymers shrink less in the direction of flow because the fibers line up in this direction; the shrinkage in the cross-flow direction is two to three times more than in the flow direction. High service temperatures can cause shrinking in some semi-crystalline materials. Fillers, or additives, are used to tailor certain properties of the composite such as density, color, flame/smoke retardance, moisture resistance, and dimensional stability. Most thermoplastics can be recycled.

Thermosets

If you are a do-it-yourself type, you have Araldite in your toolbox – two tubes, one a sticky resin, the other an even more sticky hardener. Mix and warm them and they react to give a stiff, strong, durable polymer, stuck to whatever it was put on. Araldite typifies thermosets – resins that polymerize when catalyzed and heated; when reheated they do not melt – they degrade. The common thermosets are listed in the table here. The first commercial thermoset was Bakelite, a trade-name for a phenolic resin. Polyurethane thermosets are produced in the highest volume; polyesters come second; phenolics, epoxies, and silicones follow, and – not surprisingly – the cost rises in the same order. Epoxies are two-part system that – when mixed – undergo a mildly exothermic reaction that produces cross-linking. Phenolics are cross-linked

Thermoplastic Polymers

Acrylonitrile-butadiene-styrene (ABS)
Cellulose
Ionomers
Polyamide (Nylon, PA)
Polycarbonate (PC)
Polyetheretherketone (PEEK)
Polyethylene (PE)
Polymethylmethacrylate (PMMA)
Polyoxymethylene (POM)
Polypropylene (PP)
Polystyrene (PS)
Polytetrafluoroethylene (PTFE)
Polyvinylchloride (TPPVC)
Polyurethanes (TPPU)
Polyesters (PET, PETE, PBT)

Thermosetting Polymers

Epoxy
Phenolic
Polyester
Polyurethane (tSPU)
Polyvinylchloride (tSPVC)

Elastomers

Acrylic elastomers
 Butyl rubbers (NR)
 Chlorinated elastomers (Neoprene)
 Ethylene-propylene (EPDM)
 Ethylene-vinyl-acetate (EVA)
 Fluorocarbon elastomers (Viton)
 Isoprene
 Natural rubber
 Nitrile (NBR, buna-N)
 Polybutadiene elastomers
 Polysulphide elastomers
 Silicone
 Styrene-butadiene (SBS)
 Thermoplastic elastomers (TPE, TPO)

Polymers That Are Foamed

Phenolic
 Polyethylene
 Polypropylene
 Polystyrene
 Polyurethane

by the application of heat or heat and pressure. Vulcanization of rubber, catalyzed by the addition of sulfur, can change the soft rubber of a latex glove to the rigid solid of ebonite, depending on the level of cross-linking. Once shaped, thermosets cannot be reshaped.

Thermosets have greater dimensional stability than thermoplastics; they are used where there is a requirement for high-temperature resistance and little or no creep. Most are hard and rigid, but they can be soft and flexible (like natural and synthetic rubber, as described above). Phenolics are most used where close-tolerance applications are necessary, polyesters (often combined with glass fibers) where high strength with low shrinkage is wanted.

Thermosets are shaped by compression molding, resin transfer molding, injection molding, pultrusion, and casting. They duplicate the mold finish and are relatively free from flow lines and sink marks, depending on the mold design – high gloss, satin, or sandblasted finishes are possible, and raised lettering can be molded in. Molding can be adapted to low volume production by using low-cost methods; but higher production volumes, up to a million or greater, are economical only with expensive molds that allow fast heating, cooling, and extraction. Phenolics can be molded only in black or brown; urea, melamine, alkyd, and polyester compounds are available in a wider range of colors. The fluidity of some thermosets before molding allows them to take up fine detail, and to penetrate between fibers to create composites. Most high performance polymer composites have thermosetting matrix materials. Dough and sheet molding compounds (DMC and SMC) use polyesters; filament-wound carbon or glass use epoxies as the matrix to give the highest performance of all. Thermosets cannot be recycled.

Elastomers

Elastomers were originally called “rubbers” because they could rub out pencil marks – but that is the least of their many remarkable and useful properties. Unlike any other class of solid, elastomers remember their shape when they are stretched – some, to five or more times their original length – and return to it when released. This allows conformability – hence their use for seals and gaskets. High damping elastomers recover slowly; those with low damping snap back, returning the energy it took to stretch them – hence their use for springs, catapults, and bouncy things. Conformability gives elastomers high friction on rough surfaces, part of the reason (along with comfort) that they are used for pneumatic tires and footwear. Elastomers are easy to foam, giving them the comfort of cushions, and increasing even further their ability to conform to whatever shape is pressed against them.

Almost all engineering solids have elastic moduli (measuring their stiffness) between 1 and 1000 GPa. Elastomers are much less stiff – between 0.0001 and 1 GPa. This low stiffness, their ability to stretch, and to remember their original shape all derive from their structure. The molecules in an elastomer are long chains of linked carbon (or, in silicones, silicon-oxygen chains), with hydrogen, nitrogen, chlorine, or fluorine attached to the sides. The carbon atoms that link to form the chain are strongly bonded to each other, but the side branches of one molecule are only weakly attracted to those of another – indeed, at room temperature these molecule-to-molecule bonds in an elastomer have melted. In this state the elastomer is a very viscous liquid, its molecules tangled like a plate of cooked spaghetti, and it can be molded. It is then cured; the curing creates occasional strong links between molecules, freezing the tangle in its molded shape. Most of the length of any one molecule can still slither over its neighbors, allowing stretch, but when released, the widely spaced attachment points pull the tangle back to its original shape. In the case of natural rubber, curing is achieved by heating with sulfur (“vulcanization”); in synthetic rubbers the curing process is more complex but the effect is the same. This means that elastomers are thermosets – once cured, you can’t remold them, or reshape or recycle them, a major problem with car tires. Tires are the single biggest use of elastomers; the second is footwear, followed by industrial rollers, belts, cushions, clothes, and sports equipment. Elastomers are processed by casting, calendering, extrusion, and foaming.

There are probably more than 1000 grades of elastomer. The simpler ones contain only carbon, hydrogen, nitrogen, and oxygen (hydrocarbon elastomers). They tend to be vulnerable to oil, chemicals, and UV radiation. Filling with carbon-black (soot) helps protect against UV. Replacing some of the hydrogens with chlorine or fluorine (chloro/fluorocarbon elastomers) gives greater chemical stability. Even greater stability comes with replacing carbon by silicon (silicone elastomers), but they are expensive. Elastomers – as we have said – are thermosets, but tricks can be used to make them behave in some ways like thermoplastics. Blending or co-polymerizing elastomer molecules with a thermoplastic like polypropylene, PP, gives – if done properly – separated clumps of elastomer stuck together by a film of PP (Santoprene). The material behaves like an elastomer, but if heated so that the PP melts, it can be remolded and even recycled.

Design Notes

Attitudes toward polymers – plastics – have changed over the last 70 years. In the 1930s, when Bakelite was already established and cellophane, PVC, polystyrene, Plexiglas, and nylons were first introduced, their freedom of form and color inspired young designers. By the 1950s they were plentiful and cheap, and the low cost of both the materials and of their processing led to an era of cheap, poorly designed disposable products that gave plastics a bad name. Since 1970, however, the use of polymers in high-quality clothing, footwear, household products, and transportation systems has created a market served by innovative designers exploiting the immense range of form, color, surface finish, translucency, transparency, toughness, and flexibility of modern polymers. Their combination with fillers and fibers (glass, carbon, Kevlar) has given a range of light materials with stiffness and strength comparable to that of metals, allowing their penetration into the automobile, aerospace, and marine sectors.

Polymers are familiar as fibers (nylon and polyester thread, polypropylene rope), as film (clinging film, polyethylene bags), as bulk moldings (plastic garden furniture, computer housings), and as foam (polystyrene packaging, bicycle helmets). Polymer fibers are much stronger and stiffer than their equivalent in bulk form because the drawing process by which they are made orients the polymer chains along the fiber axis. Thus, drawn polypropylene, polyethylene – and above all, aramid – have strengths, relative to their weight, that exceed that of steel. Polymer fibers are rarely used on their own. They are used as reinforcement in polymer resin, woven into fabrics, or bundled for ropes.

Ease of molding allows shapes that, in other materials, could only be built up by expensive assembly methods. Their excellent workability allows the molding of complex forms, allowing cheap manufacture of integrated components that previously were made by assembling many parts. Blending allows properties to be “tuned” to meet specific design requirements of stiffness, strength, and processability. Smaller additions allow other adjustments of properties: plasticizing additives give leathery behavior; flame retardant additives reduce flammability. Some polymers, like PPO, are used almost exclusively in blends (PPO is difficult to process on its own); others are used in “pure” form.

Many polymers are cheap both to buy and to shape. Most resist water, acids, and alkalis well, though organic solvents attack some. All are light, and many are flexible. Their color and freedom of shape allows innovative design. Thermoplastics can be recycled, and most are non-toxic, though their monomers are not. The properties of polymers change rapidly with temperature. Even at room temperatures many creep, slowly changing their shape under load; and when cooled they may become brittle. Polymers generally are sensitive to UV radiation and to strongly oxidizing environments, requiring special protection. They have exceptionally good electrical resistance and dielectric strength. When foamed they provide insulation materials with a thermal conductivity almost as low as that of still air.

The basis of polymers in oil (a non-renewable resource) and the difficulty of disposing of them at the end of their life (they don't easily degrade) has led to a view that polymers are environmentally unfriendly. There is some truth in this, but the present problems are



Want to Recycle?

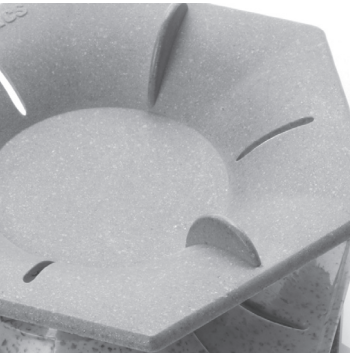
Then these are important. Polymers are hard to identify. These marks identify the six most common polymers.

Polymer Classes

More than 95% of all polymer consumption comes from these five classes.



Recycled Polyethylene



Molded and Bead-Blasted ABS

Ethylene						
tpPE	elPE	PE Blends	PE Foam	PE Fiber	PE Film	Polypropylene
HDPE	TPO	PE/PP				PP Foam
LDPE	EPDM					PP Blends
LLDPE	CPE					PP Fiber
VLDPE	EVA					PP Film
Ionomers						

Styrene				
tpPS	elPS	PS Foam	PS Blends	ABS
HIPS	SEBS			SAN
	SBR			ASA
				ABS Blends
				ABS Foam

Vinyl Chloride		
elPVC	tpPVC	PVC Film

Urethane			
PU Foam	tsPU	tpPU	elPU

Esters				
tpPolyester	tsPolyester	elPolyester	Polyester Fiber	Polyester Film
PET	UP	TPES		
PBT				
PETE				

soluble. Using oil to make polymers is a better primary use than just burning it for heat; the heat can still be recovered from the polymer at the end of its life. There are alternatives to oil: polymer feed stocks can be synthesized from agricultural products (notably starch and sugar, via methanol and ethanol). And thermoplastics – provided they are not contaminated – can be (and are) recycled.

Polymers and composites based on them are the most rapidly growing sector of the market for structural and decorative material. Research on biodegradable polymers, and polymers synthesized from agricultural by-products such as lignin, is leading to new generations of eco-friendly products. Polymers with greater thermal stability, higher stiffness, strength, and toughness are all under development. Most exciting is the increasing ability to build functionality into polymers. Electro-active polymers carry an electric dipole moment and thus are influenced by an electric field; they can be used for microphones and loud speakers. Optically-active polymers emit light when excited electrically; they allow large area, flexible, displays. High-temperature polymers, though expensive, are sufficiently stable that they can be used for inlet manifolds and other components on internal combustion engines.

There are many types of polymers and the relationships between each other can be confusing. Some of these relationships are shown above. Polyethylene is the simplest of the polyolefins but even it can be manipulated in many ways. It starts life as ethylene, C_2H_4 .

Polymerization gives chains of $\text{CH}_2\text{-CH}_2\text{-CH}_2\text{-...}$. Depending on the catalyst, the chains can be short or long, linear or branched. Once polymerized, they can be blended, foamed, and drawn into fibers or film. And by starting with propylene, C_3H_6 , instead of ethylene, a similar diversity of polypropylenes can be synthesized.

Polystyrene has similarly complicated possibilities; it begins as styrene-ethylene with one hydrogen replaced by a benzene ring. It can be modified as a thermoplastic or elastomer, foamed or blended; and, by chemical modifications, become ABS and its derivatives.

Polyesters, PVCs, and polyurethanes, too, have many personalities; they overlap the bounds of thermoplastic, elastomer, and thermoset more than other resins. PVCs can be a thermoplastic or elastomer; polyurethanes and polyesters can be any of the three; in addition, polyurethane can be foamed and polyester can be made into film or fibers. This diversity can be confusing, but the wide range of properties it allows is the source of great freedom of design.

Polymer Composites

Composites are one of the great material developments of the 20th century. Those with the highest stiffness and strength are made of continuous fibers (glass, carbon, or Kevlar, an aramid) embedded in a thermosetting resin (polyester or epoxy). The fibers carry the mechanical loads, while the matrix material transmits loads to the fibers and provides ductility and toughness as well as protecting the fibers from damage caused by handling or the environment. It is the matrix material that limits the service temperature and processing conditions. Polyester-glass composites (GFRPs) are the cheapest; epoxy-carbon (CFRPs) and Kevlar-epoxy (KFRPs) the most expensive. A recent innovation is the use of thermoplastics as the matrix material, either in the form of a co-weave of cheap polypropylene and glass fibers that is thermoformed, melting the PP, or as expensive high-temperature thermoplastic resins such as PEEK that allow composites with high temperature and impact resistance. If continuous fiber CFRPs and GFRPs are the kings and queens of the composite world, the ordinary workers are polymers reinforced with chopped glass or carbon fibers, or with particulates (fillers) of silica sand, talc, or wood flour. They are used in far larger quantities, often in products so ordinary that most people would not guess that they were made of a composite: body and interior panels of cars, household appliances, furniture, and fittings. It would, today, be hard to live without them.

The properties of long fiber composites are strongly influenced by the choice of fiber and matrix and the way in which these are combined: fiber-resin ratio, fiber length, fiber orientation, laminate thickness, and the presence of fiber-resin coupling agents to improve bonding. Glass offers high strength at low cost; carbon has very high strength, stiffness, and low density; Kevlar has high strength and low density, is flame retardant and transparent to radio waves (unlike carbon). Polyesters are the most widely used matrices as they offer reasonable properties at relatively low cost. The superior properties of epoxies and the temperature performance of polyimides can justify their use in certain applications, but they are expensive. The strength of a composite is increased by raising the fiber-resin ratio, and orienting the fibers parallel to the loading direction. The longer the fibers, the more efficient is the reinforcement at carrying the applied loads, but shorter fibers are easier to process and hence cheaper. Increased laminate thickness leads to reduced composite strength and modulus as there is an increased likelihood of entrapped voids. Coupling agents generally increase tensile strength. Environmental conditions affect the performance of composites: fatigue loading, moisture, and heat all reduce allowable strength.

Polymer Composites

CFRP
GFRP
KFRP



Tangled Cellulose Fibers



PTFE-coated Glass Fibers

Metals

Aluminum alloys
Copper alloys
Magnesium alloys
Nickel alloys
Steels – carbon
Steels – low alloy
Steels – stainless
Titanium alloys
Zinc alloys

Design Notes

Polymer composites can be formed by closed or open mold methods. All the closed mold methods produce fiber orientation parallel to the mold surfaces (for extrusion, it is parallel to the inside surface of the orifice die). Of the open mold methods, all allow multidirectional fiber orientation parallel to the mold or mandrel, except pultrusion, where the fibers are oriented parallel to the laminate surface and the mold plates, and calendering, where they are parallel to the sheet surface. Lay-up methods allow complete control of fiber orientation; they are used for large one-off products that do not require a high fiber-resin ratio. Lamination and calendering form sheets, pultrusion is used to make continuous shapes of constant cross-section, and filament winding produces large hollow items such as tubes, drums, or other containers.

Joints in long-fiber composite materials are sources of weakness because the fibers do not bridge the joint. Two or more laminates are usually joined using adhesives and, to ensure adequate bonding, an overlap length of 25 mm for single- and double-lap joints or 40–50 mm for strap, step, and scarf joints is necessary. Holes in laminates dramatically reduce the failure strength making joining with fasteners difficult. Composite manufacture is labor intensive. It is difficult to predict the final strength and failure mode because defects are easy to create and hard to detect or repair.

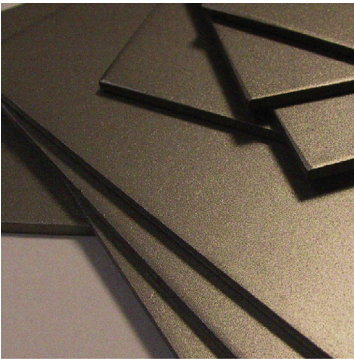
Metals

Most of the elements in the periodic table are metals. Metals have “free” electrons – electrons that flow in an electric field – so they conduct electricity well, they reflect light and – viewed with the light behind them – they are completely opaque. The metals used in product design are, almost without exception, alloys. Steels (iron with carbon and a host of other alloying elements to make them harder, tougher, or more corrosion resistant) account for more than 90% of all the metals consumed in the world; aluminum comes next, followed by copper, nickel, zinc, titanium, magnesium, and tungsten.

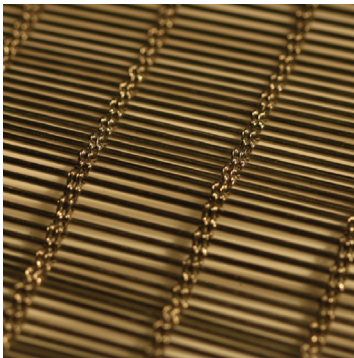
Design Notes

Compared to all other classes of material, metals are stiff, strong, and tough, but they are heavy. They have relatively high melting points, allowing some metal alloys to be used at temperatures as high as 2200 C. Only one metal – gold – is chemically stable as a metal; all the others will, given the chance, react with oxygen, or sulfur to form compounds that are more stable than the metal itself, making them vulnerable to corrosion. There are numerous ways of preventing or slowing this to an acceptable level, but they require maintenance. Metals are ductile, allowing them to be shaped by rolling, forging, drawing, and extrusion; they are easy to machine with precision; and they can be joined in many different ways. This allows a flexibility of design with metals that is only now being challenged by polymers.

The development of metals and alloys continues. Superplastic alloys have the unique property that, in sheet form, they can be vacuum or thermoformed like thermoplastics. Shape-memory alloys have the capacity to remember their initial shape even when deformed very heavily, so that they spring back like a rubber – they are used in thermostats, and as the frames for eye glasses, brassieres, and small actuators. Metal matrix composites (such as aluminum with silicon carbide) extend the property range of metals, usually to make them stiffer, lighter, and more tolerant of heat, but their cost limits their applications. Techniques for foaming metals are emerging that have the potential to capture new market. Nonetheless, the status of metals has been eroded during the past few decades by other materials: polymers in small scale structures like household appliances,



Titanium Sheet



Woven Stainless Steel Wire

polymer-based composites in cars, aircraft, and boats; and ceramics in certain engine parts and cutting blades. But as Guy Nordenson, of the engineering firm Arup, observes, “Materials development and usage are historically cyclical. Work with metals is probably more out of touch than it is behind.”

Primary production of metals is energy intensive. Many, among them aluminum, magnesium, and titanium, require at least twice as much energy per unit weight (or five times more per unit volume) than commodity polymers. But metals can generally be recycled, and the energy required to do so is much less than that required for primary production. Some are toxic, particularly the heavy metals – lead, cadmium, mercury. Some, however, are so inert that they can be implanted in the body: stainless steels, cobalt alloys, and certain alloys of titanium, for example.

Ceramics

Ceramics are materials both of the past and of the future. They are the most durable of all materials – ceramic pots and ornaments survive from 5000 BC. And it is their durability, particularly at high temperatures, that generates interest in them today. They are exceptionally hard (diamond – a ceramic – is the hardest of them all) and can tolerate higher temperatures than any metal. Ceramics are crystalline (or partly crystalline) inorganic compounds; they include both traditional, pottery-based ceramics, and the high performance technical ceramics. All are hard and brittle, have generally high melting points and low thermal expansion coefficients, and most are good electrical insulators. Traditional ceramics, based on clay, silica, and feldspar, are soft and easily molded before they are fired; firing creates a glassy phase that binds the other components together to create brick, stoneware, porcelain, and tile. Technical ceramics consist of pure or nearly pure compounds, synthesized by chemical reactions; the commonest are alumina, silicon carbide, silicon nitride, boron carbide, boron nitride, and tungsten carbide.

Ceramics have certain unique properties. Their low atomic packing factors and high melting points give them a low expansion coefficient. Those that are pure and completely crystalline have a high thermal conductivity; impurities and glassy phases greatly reduce it. When perfect they are exceedingly strong, but tiny flaws, hard to avoid, propagate as cracks when the material is loaded in tension or bending, drastically reducing the strength; the compressive strength, however, remains high (8–18 times the strength in tension). Impact resistance is low and stresses due to thermal shock are not easily alleviated by plastic deformation so large temperature gradients or thermal shock can cause failure.

Design Notes

The size of commercial ceramic parts can range from small components like spark plug insulators to large nose cones for re-entry vehicles. The high firing temperatures prevent metal inserts being molded-in to ceramics. Shapes should be kept as simple as possible, with liberal tolerances. Shrinkage during drying and firing can be as much as 25%. Edges and corners should have generous radii, large unsupported sections, and undercuts should be avoided, symmetrical shapes and uniform wall thicknesses are best, with a draft angle of at least 5 degrees.

Most technical ceramics start as powders that are pressed, extruded, injection molded, or cast, using a polymer binder. The resulting “green” part is machined or ground to shape, dried and fired (“sintering”). Metal can be joined to ceramic by adhesives, soldering, brazing, or shrink fitting (as long as the metal is on the outside, in tension). Brazing is stronger than adhesives or soldering and more temperature resistant but requires a metallized

Ceramics and Glass

- Alumina
- Boron carbide
- Silicon carbide
- Tungsten carbide
- Borosilicate glass
- Silica glass
- Soda lime glass
- Glass ceramic



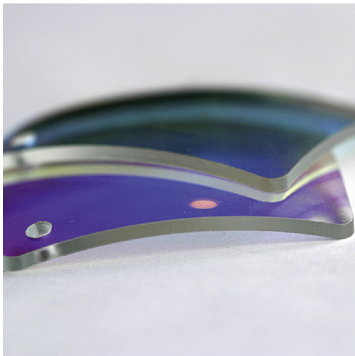
Alumina Foam



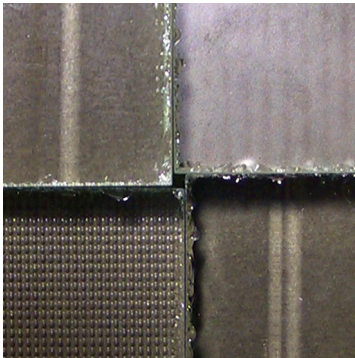
Terracotta

coating as a base for the brazing alloy. Glaze bonding or diffusion bonding allows joining ceramic to ceramic or metal to ceramic. Glazes can be applied to ceramics for a smooth, glossy surface; patina surfaces are also possible.

Traditional ceramics are familiar as brick, tile, white ware (toilets, baths, sinks), and pottery. Technical ceramics are used as bearings, turbine blades, cams, cutting tools, extrusion dies, nozzles, seals, filters, crucibles and trays, electrical insulators, substrates, and heat sinks for electronic circuitry.



Dichroic-Coated Glass



Textured Glass

Glass

Discovered by the Egyptians and perfected by the Romans, glass is one of the oldest of man-made materials. For most of its long history it was a possession for the rich – as glass beads, ornaments, and vessels, and, of course, glass as glaze on pottery. Its use in windows started in the 15th century but it was not wide spread until the 17th. Now, of course, it is so universal and cheap that – as bottles – we throw it away. Glass is a mix of oxides, principally silica, SiO_2 , that does not crystallize when cooled after melting. When pure it is crystal-clear, but it is easy to color by adding metal oxides.

Design Notes

Glass is formed by pressing, blow molding, centrifugal casting, drawing or rolling, and must be cooled at a controlled rate to avoid residual stresses. It can be strengthened by rapid air cooling of the surface – known as “tempered” glass; tensile stresses build up inside the glass, creating compressive stresses in the surface, increasing the impact strength by a factor of 4. Electric light bulbs are molded on a machine that converts a fast moving ribbon of glass into as many as 10,000 bulbs per hour. Glass is joined by glaze (melt) bonding, clamping, or adhesives. A silver coating gives nearly 100% reflection of visible light – this is used for most mirrors. A gold mirror coating can reflect 90% of IR radiation.

Adding metal oxides produces colored glass. Nickel gives a purple hue, cobalt a blue, chromium a green, uranium a green-yellow, iron a green-blue. The addition of iron gives a material that can absorb wavelengths in the infrared range so that heat radiation can be absorbed. Colorless, non-metallic particles (fluorides or phosphates) are added from 5 to 15% to produce a translucent or an almost opaque white opalescence in glass and glass coatings. Photochromic glass changes color when exposed to UV (it sometimes fades when heated); photosensitive glass turns from clear to opal when exposed to UV or heated. Filter glass protects from intense light and UV radiation – it is used in visors for welding. Dichroic coatings and thin laminations give color modulation.

Fibers

Fibers clothe us, carpet us, cushion us, keep us warm, and protected. They are the substance of thread, of rope, of fabrics, of textiles, and of fiber-reinforced composites. Fibers have the unique virtue of being strong yet flexible – pull them, and they resist, flex them, and they comply. Spin them into rope or weave them into cloth and these inherit the same properties.

Technical Fibers

Metal fibers can be made – they are used to reinforce car tires – but metals are heavy. More interesting are those that are light, stiff, and strong. Here are some that, through their strength and flexibility, allow the creation of novel materials. The rapid expansion

of fiber-reinforced composites in the 20th century give three man-made fibers – aramid, carbon, and glass – prominence as engineering materials. All three are stiff and strong, and two of them (aramid and carbon) are exceptionally light, making them ideal reinforcement for aerospace structures, sports equipment and, increasingly, ground transport systems. Glass fiber is cheap, making composites containing it viable for cars and household products. Carbon and aramid are more expensive, limiting their use to higher-value applications.

Vegetable-derived Fibers

Natural fibers have been used to make ropes, fabrics, and shelters for thousands of years. They still are. Protein fibers (wools, hairs) are derived from animals. Vegetable fibers are based on cellulose and are found in stem (bast), leaf, seed, and fruit. Many derive from fast growing plants, making them potentially renewable. Their properties are compared with those of man-made fibers in Figures 11.8 and 11.9. No natural fiber matches carbon, Kevlar, or drawn steel for absolute strength and modulus, but because the densities of natural fibers are low, their specific properties are much more attractive. This has led to efforts to use them as reinforcement for panels for cars and trucks, an application we return to in a later section. First, some background on natural fibers. They are listed below in alphabetical order.

Coir (from Malayalam *kayar*, cord) is a coarse fiber extracted from the hairy outer shell of a coconut. There are two sorts. White coir, harvested from unripe coconuts, is spun to yarn that is used in mats or rope. Brown coir, from fully ripened coconuts, is thicker and stronger than white coir. It is used in mats, brushes, and sacking. Pads of brown coir sprayed with latex (rubberized coir) is used as upholstery padding in cars. The coir fiber is relatively water-proof and is one of the few natural fibers resistant to damage by salt water.

Cotton is fiber from the blossom of the plant *Gossypium*. There are many species, all chemically identical (95% cellulose with a little wax) but differing in fiber length and slenderness. Cotton is used to make a great range of different fabrics with wonderful names, many deriving from the country or town of their origin: voile, calico, gingham, muslin, crepe, damask, cambric, organdie, crinoline, twill, sailcloth, canvas. They differ in the quality of the fiber and the nature of the weave.

Flax is a fiber from the stalk of the linseed plant, *Linum usitatissimum*. As with hemp, the fibers are freed from the stalk by retting, an exceptionally smelly process. Flax is used to make linen and rope, valued for their strength and durability. Flax has been used as a reinforcement for polymer-matrix composites.

Hemp comes from the weed *Cannabis Sativa*. The hemp fibers, like those of flax, are freed from the stalk by a retting process (for “retting” read “rotting”). The properties of hemp resemble those of cotton. It is used for rope and coarse fabric, and is a potential reinforcement natural fiber reinforced composites. Hemp is valued for its great strength. It is used for cord, rope, sacks, packaging and, increasingly, as a reinforcement in polymers. Other rope materials, like abaca, are more water resistant and have replaced hemp in marine applications. Hemp-reinforced composites cannot at present be recycled, but the hemp is a renewable resource and the energy overhead in producing it is low – far lower than carbon or Kevlar. Typical Uses: Rope and strong fabric; reinforcement in polymer-matrix composites.

Jute is a long, soft, shiny vegetable fiber made from the stems of plants in the genus *Cortecorus*, family *Malvaceae*. It is one of the cheapest of natural fibers and is second only to cotton in amount produced and variety of uses. It is spun into coarse, strong threads, and woven to make sack-cloth, hessian, or burlap. There is interest in using jute as reinforcement in composites, replacing glass.



Kenaf (*Hibiscus cannabinus*) is a fast-growing stem-fiber used to make industrial textiles, ropes, and twines. Emerging uses of kenaf fiber include engineered wood, insulation, and clothing-grade cloth and as a reinforcement in polymer-matrix composites.

Palmyra Palm (*Borassus*) is a genus of fan palms, native to tropical regions of Africa, Asia, and New Guinea. Palm fiber (sometimes called “vegetable horsehair”) is derived from its leaves. The fibers are springy and strong, making good stuffing for furniture and mattresses.

Ramie (*Boehmeria nivea*) comes from the stem of a flowering plant in the nettle family. It is one of the strongest natural fibers. It is used for cordage and thread and woven into fabrics for household furnishings (upholstery, canvas) and clothing, frequently in blends with other textile fibers.

Sisal fiber is derived from an agave, *Agave sisalana*. It is valued for cordage because of its strength, durability, ability to stretch, affinity for certain dyestuffs, and, like coir, it is resistance to deterioration in saltwater. The higher-grade fiber is converted into yarns for the carpet industry. Sisal is now used as a reinforcement in polymer-matrix composites.

Animal-derived Fibers

Animal life, from an energy point of view, is high-maintenance. That means that materials derived from animals have a larger embodied energy than those of the vegetable world.

Wools are keratin, the hair or fleece of the sheep, alpaca, rabbit (angora), camel (camel hair), certain goats (mohair, Kashmir), and llamas (vicuna). It is hard wearing (as in wool carpets) and an excellent thermal insulator (as in wool sweaters and blankets). Wool is woven in many different ways to give cloth, tweed, plaid, flannel, or worsted. Wool fabrics are dirt-resistant, flame-resistant, and, in many weaves, resistant to wear and tearing. But keratin is a protein, easily digested by the larvae of moths if steps are not taken to stop them.

Silks, too, are proteins, the fibers spun by the silk worm to wrap and insulate its cocoon and the spider to trap its prey. Silk is remarkable for its strength and extendability. The combination imparts energy-absorbing qualities that make spiders webs so effective. It is the material of high-altitude balloons, parachutes, and the clothing of film stars and empresses.

Further reading

Amato, I. (1997) "Stuff, the Materials the World Is Made Of," Harper Collins, New York, NY, USA. ISBN 0-465-08328-5. (Amato is a science writer for the news media, and he does it exceptionally well. This is in the news media style – readable, highlighting potential, much not yet realized, and heavily dependent on interviews with those who've agreed to do it.)

Braddock, S.E. and O'Mahony, M. (1998) "Techno Textiles: Revolutionary Fabrics for Fashion and Design," Thames and Hudson. ISBN 0-500-28096-7. (This book presents information about polymer textiles and fabrics from the fashion industry to a wider audience of design.)

Cardarelli, F. (1987) "Materials Handbook," Springer, London. ISBN 1-85233-168-2. (As a handbook of technical material information, this book provides information on metals, semi-conductors, super-conductors, ceramics, glasses, polymers, elastomers, minerals, rocks, and woods.)

Colling, D.A. and Vasilos, T. (1995) "Industrial Materials," Volume I and II, Prentice-Hall, Englewood Cliffs, NJ, USA. ISBN 0-02-323560-8 and 0-02-323553-5. (A set of books that briefly introduce materials – metals, polymers, ceramics, and composites.)

Dieter, G. (Ed.), (1997) "Asm Handbook – Volume 20 Materials Selection And Design," Asm International, Materials Park, oh, usa. isbn 0-87170-386-6. (One of the latest in a series that covers a wide range of technical data about materials, now available on CD for ease of browsing and searching.)

Emmley, J. (1998) "Molecules at an Exhibition," Oxford University Press, Oxford, UK. ISBN 0-19-286206-5. (Popular science writing at its best: intelligible, accurate, simple, and clear. The book is exceptional for its range. The message is that molecules – sometimes meaning materials – influence our health, our lives, the things we make and the things we use.)

Fiell, C. and Fiell, P. (2000) "Industrial Design A-Z," Taschen GmbH, Cologne, Germany. ISBN 3-8228-6310-5. (A summary of key designers and design firms that includes profiles of particular design styles and materials that have had significant influence: aluminum, Bakelite, carbon fiber, ceramics, chromium, plastics, plywood, Pyrex, rubber, and tubular metal.)

Harper, C.A. (1999) "Handbook of Materials for Product Design," McGraw-Hill, New York, NY, US. ISBN 0-07-135406-9. (This handbook contains many technical details for steels, aluminum, titanium, polymers, composites, natural and synthetic rubber, elastomers, ceramics, and glasses; there is also some information on surface processes (metal coatings in particular), joining polymers and elastomers and recycling materials.)

Lesko, J. (1999) "Industrial Design: Materials and Manufacturing Guide," John Wiley & Sons, New York, NY, USA. ISBN 0-471-29769-0. (A summary of materials and processes that are of interest to industrial designers, focused on the relevant technical information for each.)



Attributes of Polyethylene

Price, \$/kg	1.10-4.00
Density, mg/m ³	0.92-1.4

Technical Attributes

El. modulus, GPA	0.03-1.4
Elongation, %	10-1400
Fr. toughness, MPA·m ^{1/2}	0.40-5.16
Vickers hardness, H _v	5-8
Yld. strength, MPA	8-31
Service temp., C	-40-100
Specific heat, J/kg·K	1559-1916
Th. conduct., w/m·K	0.12-0.50
Th. expansion, 10 ⁻⁶ /K	106-450

Eco-Attributes

Energy content, MJ/kg	104-114
Carbon footprint, CO ₂ (kg/kg)	2.8
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	3-7
Muffled (o), Ringing (1o)	1-3
Soft (o), Hard (1o)	5-7
Warm (o), Cool (1o)	4-5
Gloss, %	5-136

Features (Relative to Other Polymers)

- Easily molded
- Durable
- Low cost

Polyethylene (PE)

What Is It? Polyethylene (CH₂)_n, first synthesized in 1933, looks like the simplest of molecules, but the number of ways in which the -CH₂- units can be linked is large. It is the first of the polyolefins, the bulk thermoplastic polymers that account for a dominant fraction of all polymer consumption. Polyethylene is inert, and extremely resistant to fresh and salt water, food, and most water-based solutions. Because of this it is widely used in household products and food containers.

Design Notes PE is commercially produced as film, sheet, rod, foam, and fiber. Drawn PE fiber has exceptional mechanical stiffness and strength, exploited in geo-textile and structural uses. Polyethylene is cheap, and particularly easy to mold and fabricate. It accepts a wide range of colors, can be transparent, translucent, or opaque, has a pleasant, slightly waxy feel, can be textured or metal coated, but is difficult to print on. PE is a good electrical insulator with low dielectric loss, so suitable for containers for microwave cooking.

Typical Uses Oil containers, street bollards, milk bottles, toys, beer crates, food packaging, shrink wrap, squeeze tubes, disposable clothing, plastic bags, Tupperware, chopping boards, paper coatings, cable insulation, artificial joints, and as fibers – low cost ropes and packing tape reinforcement.

Competing Materials Polypropylene, polystyrene, ABS, SAN, EVA, elPVC; aluminum as foil and packaging; steel sheet as cans.

The Environment PE is FDA compliant – indeed it is so non-toxic that it can be embedded in the human body (heart valves, hip-joint cups, artificial artery). PE, PP, and PVC are made by processes that are relatively energy-efficient, making them the least energy intensive of commodity polymers. PE can be produced from renewable resources – from alcohol derived from the fermentation of sugar or starch, for instance. Its utility per kilogram far exceeds that of gasoline or fuel-oil, so that production from oil will not disadvantage it in the near future. Polyethylene is readily recyclable if it has not been coated with other materials, and – if contaminated – it can be incinerated to recover the energy it contains.

Technical Notes Low density polyethylene (LDPE), used for film and packaging, has branched chains which do not pack well, making it less dense than water. Medium (MDPE) and high (HDPE) density polyethylenes have longer, less branched chains, making them stiffer and stronger; they are used for containers and pipes. Linear low density polyethylene (LLPDE) is less resistant to organic solvents, but even this can be overcome by converting its surface to a fluoro-polymer by exposing it to fluorine gas. Treated in this way (when it is known as “Super PE”) it can be used for petrol tanks in cars and copes with oil, cleaning fluid, cosmetics, and that most corrosive of substances: cola concentrate. Very low density polyethylene (VLDPE) is similar to EVA and plasticized PVC.

Polypropylene (PP)

What Is It? Polypropylene, PP, first produced commercially in 1958, is the younger brother of polyethylene – a very similar molecule with similar price, processing methods, and application. Like PE it is produced in very large quantities (more than 30 million tons per year in 2000), growing at nearly 10% per year, and like PE its molecule lengths and side branches can be tailored by clever catalysis, giving precise control of impact strength, and of the properties that influence molding and drawing. In its pure form polypropylene is flammable and degrades in sunlight. Fire retardants make it slow to burn and stabilizers give it extreme stability, both to UV radiation and to fresh and salt water and most aqueous solutions.

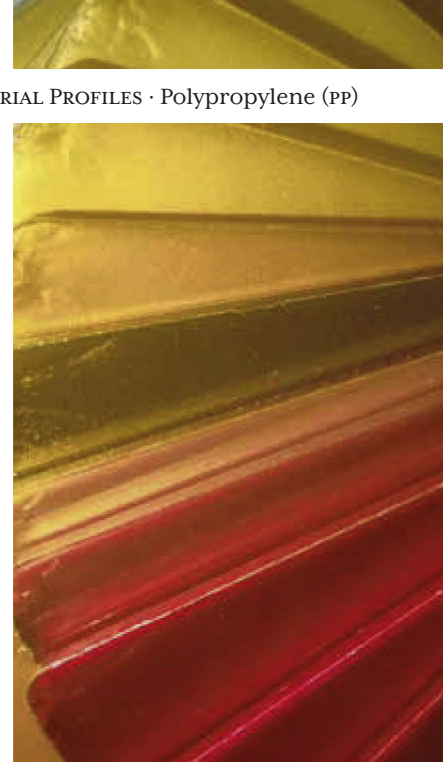
Design Notes Standard grade PP is inexpensive, light, and ductile but it has low strength. It is more rigid than PE and can be used at higher temperatures. The properties of PP are similar to those of HDPE but it is stiffer and melts at a higher temperature (165–170°C). Stiffness and strength can be improved by reinforcing with glass, chalk, or talc. When drawn to fiber PP has exceptional strength and resilience; this, together with its resistance to water, makes it attractive for ropes and fabric. It is more easily molded than PE, has good transparency and can accept a wider, more vivid range of colors. Advances in catalysis promise new co-polymers of PP with more attractive combinations of toughness, stability, and ease of processing. Mono-filament fibers and multi-filament yarn or rope have high abrasion resistance and are almost twice as strong as PE fibers.

Typical Uses Ropes, general polymer engineering, automobile air ducting, parcel shelving and air-cleaners, garden furniture, washing machine tanks, wet-cell battery cases, pipes and pipe fittings, beer bottle crates, chair shells, capacitor dielectrics, cable insulation, kitchen kettles, car bumpers, shatter proof glasses, crates, suitcases, artificial turf, thermal underwear.

Competing Materials Polyethylene, polystyrene, ABS, SAN; aluminum as foil and packaging; steel sheet as cans.

The Environment PP is exceptionally inert and easy to recycle, and can be incinerated to recover the energy it contains. PP, like PE and PVC, is made by processes that are relatively energy-efficient, making them the least energy intensive of commodity polymers. Its utility per kilogram far exceeds that of gasoline or fuel-oil, so that production from oil will not disadvantage it in the near future.

Technical Notes The many different grades of polypropylene fall into three basic groups: homopolymers (polypropylene, with a range of molecular weights and thus properties), co-polymers (made by co-polymerization of propylene with other olefins such as ethylene, butylene, or styrene) and composites (polypropylene reinforced with mica, talc, glass powder, or fibers) that are stiffer and better able to resist heat than simple polypropylenes.



Attributes of Polypropylene

Price, \$/kg	0.90–1.00
Density, mg/m ³	0.89–0.92

Technical Attributes

El. modulus, GPa	0.90–1.55
Elongation, %	100–600
Fr. toughness, MPa·m ^{1/2}	3–4.5
Vickers hardness, H _v	6–11
Yld. strength, MPa	20.7–37.2
Service temp., °C	–40–120
Specific heat, J/kg·K	1870–1956
Th. conduct., W/m·K	0.11–0.17
Th. expansion, 10 ^{–6} /K	122–180

Eco-Attributes

Energy content, MJ/kg	76–84
Carbon footprint, CO ₂ (kg/kg)	3.1
Recycle potential	Medium

Aesthetic Attributes

Low (o), High pitch (1o)	6–7
Muffled (o), Ringing (1o)	3–4
Soft (o), Hard (1o)	6–7
Warm (o), Cool (1o)	4
Gloss, %	20–94

Features (Relative to Other Polymers)

Easily molded
Durable and tough
Low cost

**Attributes of Polystyrene**

Price, \$/kg	2.20–3.80
Density, Mg/m ³	1.04–1.05

Technical Attributes

El. modulus, GPa	2.28–3.34
Elongation, %	1.2–3.6
Fr. toughness, MPa·m ^{1/2}	0.7–1.1
Vickers hardness, H _v	9–16
Yld. strength, MPa	28.72–56.2
Service temp., °C	–18–100
Specific heat, J/kg·K	1691–1758
Th. conduct., W/m·K	0.12–0.13
Th. expansion, 10 ^{–6} /K	90–153

Eco-Attributes

Energy content, MJ/kg	101–110
Carbon footprint, CO ₂ (kg/kg)	3.8
Recycle potential	Low

Aesthetic Attributes

Low (o), High Pitch (1o)	7
Muffled (o), Ringing (1o)	4
Soft (o), Hard (1o)	7
Warm (o), Cool (1o)	4
Gloss, %	9–96

Features (Relative to Other Polymers)

Optically clear
Easily foamed
Low cost

Polystyrene (PS)

What Is It? In its simplest form PS is brittle. Its mechanical properties are dramatically improved by blending with polybutadiene, but with a loss of optical transparency. High impact PS (10% polybutadiene) is much stronger even at low temperatures (meaning strength down to –12 °C).

Design Notes PS comes in three guises: as the simple material (“general purpose PS”); as the high impact variant, blended with polybutadiene; and as polystyrene foam, the most familiar and cheapest of all polymer foams. All are FDA approved for use as food containers and packaging. General purpose PS is easy to mold. Its extreme clarity, ability to be colored, and high refractive index give it a glass-like sparkle, but it is brittle and cracks easily (think of CD cases). It is used when optical attractiveness and low cost are sought, and the mechanical loading is light: cosmetic compacts, transparent but disposable glasses, cassettes of all kinds. Medium and high impact polystyrenes trade their optical for their mechanical properties. Medium impact PS, translucent, appears in electrical switch gears and circuit breakers, coat hangers, and combs. High impact PS – a blend of PPO and PS – is opaque, but is tough and copes better with low temperatures than most plastics; it is found in interiors of refrigerators and freezers, and in food trays such as those for margarine and yogurt. PS can be foamed to a very low density (roughly one-third of all polystyrene in foamed). These foams have low thermal conduction and are cheap, and so are used for house insulation, jackets for water boilers, insulation for disposable cups. They crush at loads that do not cause injury to delicate objects (such as TV sets or to the human body), making them good for packaging.

Typical Uses Disposable cups; light fittings; toys; pens; models; in expanded form – packaging, thermal insulation, and ceiling tiles; TV cabinets; wall tiles; disposable dishes; furniture; molded parts and containers; CD covers, disposable glass, razors, hot drink cups.

Competing Materials High density polyethylene, polypropylene, and polymer-coated paper.

The Environment The flammability of PS foam, and the use of CFCs as blowing agents in the foaming process was, at one time, a cause for concern. New flame retardants allow PS foams to meet current fire safety standards, and CFC blowing agents have been replaced by pentane, CO₂, or HFCs which do not have a damaging effect on the ozone layer. PS can be recycled. The monomer, styrene, is irritating to the eyes and throat, but none survives in the polymer.

Technical Notes Polystyrene, PS, is – like PE and PP – a member of the polyolefin family of moldable thermoplastics. In place of one of the H-atoms of the polyethylene it has a C₆H₅–benzene ring. This makes for a lumpy molecule which does not crystallize, and the resulting material is transparent with a high refractive index. The benzene ring absorbs UV light, exploited in the PS screening of fluorescent lights, but this also causes the polymer to discolor in sunlight.

Acrylonitrile-Butadiene-Styrene (ABS)

What Is It? ABS is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colors. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

Design Notes ABS has the highest impact resistance of all polymers. It takes color well. Integral metallics are possible (as in GE Plastics' Magix). ABS is UV resistant for outdoor application if stabilizers are added. It is hygroscopic (may need to be oven dried before thermoforming) and can be damaged by petroleum-based machining oils. ASA (acrylic-styrene-acrylonitrile) has very high gloss; its natural color is off-white but others are available. It has good chemical and temperature resistance and high impact resistance at low temperatures. UL-approved grades are available. SAN (styrene-acrylonitrile) has the good processing attributes of polystyrene but greater strength, stiffness, and chemical and heat resistance. By adding glass fiber the rigidity can be increased dramatically. It is transparent (over 90% in the visible range but less for UV light) and has good color. Depending on the amount of acrylonitrile that is added this can vary from water white to pale yellow, but without a protective coating, sunlight causes yellowing and loss of strength, slowed by UV stabilizers. All three can be extruded, compression molded, or formed to sheet that is then shaped by vacuum thermoforming. They can be joined by ultrasonic or hot-plate welding, or bonded with polyester, epoxy, isocyanate, or nitrile-phenolic adhesives.

Typical Uses ABS: cases for computers and TVs, telephones, food mixers, vacuum cleaners, baths, shower trays, pipes, luggage shells, RV parts, shower stalls, cassette holders, automotive parts, safety hard hats, Legos, computer mice, razors, handles, shavers, chairs. SAN: telephone cases, food-processing bowls, medical syringes, mixing bowls, beakers, coffee filters, cassettes, industrial battery cases, toothbrushes, cosmetic packs, dinnerware, food containers. ASA: appliance panels and knobs, toys, medical instruments, rear view mirrors, garden tables and chairs, hose fittings, garden tools, letter boxes, boat shells, windsurfing boards.

Competing Materials High density polyethylene, polypropylene, butyl rubber, nylon.

The Environment The acrylonitrile monomer is nasty stuff, almost as poisonous as cyanide. Once polymerized with styrene it becomes harmless. Some grades of ABS are FDA compliant and can be recycled.

Technical Notes ABS is a terpolymer – one made by co-polymerizing three monomers: acrylonitrile, butadiene, and styrene. The acrylonitrile gives thermal and chemical resistance, rubber-like butadiene gives ductility and strength, the styrene gives a glossy surface, ease of machining, and a lower cost. In ASA, the butadiene component (which gives poor UV resistance) is replaced by an acrylic ester. Without the addition of butyl, ABS becomes SAN – a similar material with lower impact resistance and toughness.



Attributes of ABS

Price, \$/kg	1.50–2.80
Density, mg/m ³	1.01–1.21

Technical Attributes

El. modulus, GPa	1.1–2.9
Elongation, %	1.5–100
Fr. toughness, MPa·m ^{1/2}	1.2–4.2
Vickers hardness, H _v	6–15
Yld. strength, MPa	18.5–51
Service temp., °C	–18–90
Specific heat, J/kg·K	1386–1919
Th. conduct., W/m·K	0.18–0.33
Th. expansion, 10 ^{–6} /K	84.6–234

Eco-Attributes

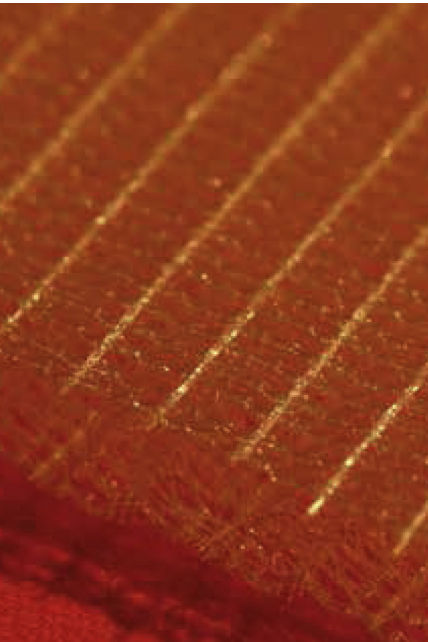
Energy content, MJ/kg	95–104
Carbon footprint, CO ₂ (kg/kg)	3.8
Recycle potential	Medium

Aesthetic Attributes

Low (o), High Pitch (10)	6–7
Muffled (o), Ringing (10)	3–4
Soft (o), Hard (10)	6–7
Warm (o), Cool (10)	4–5
Gloss, %	10–96

Features (Relative to Other Polymers)

Durable and tough
Readily colored
Easily molded



Attributes of Nylon

Price, \$/kg	2.90–11.50
Density, Mg/m ³	1–1.42

Technical Attributes

El. modulus, GPa	0.67–4.51
Elongation, %	4–1210
Fr. toughness, MPa·m ^{1/2}	0.58–8.03
Vickers hardness, H _v	6–28
Yld. strength, MPa	20.7–101.6
Service temp., C	–80–120
Specific heat, J/kg·K	1421–2323
Th. conduct., W/m·K	0.18–0.35
Th. expansion, 10 ^{–6} /K	50.4–216

Eco-Attributes

Energy content, MJ/kg	110–120
Carbon footprint, CO ₂ (kg/kg)	8.0
Recycle potential	Medium

Aesthetic Attributes

Low (o), High Pitch (1o)	6–7
Muffled (o), Ringing (1o)	3–4
Soft (o), Hard (1o)	6–7
Warm (o), Cool (1o)	4–5
Gloss, %	65–150

Features (Relative to Other Polymers)

- Strong
- Tough
- Durable

Polyamide (PA), Nylon

What Is It? Back in 1945, the war in Europe just ended, the two most prized luxuries were cigarettes and nylons. Nylon (PA) can be drawn to fibers as fine as silk, and was widely used as a substitute for it. Today, newer fibers have eroded its dominance in garment design, but nylon-fiber ropes, and nylon as reinforcement for rubber (in car tires) and other polymers (PTFE, for roofs) remains important. It is used in product design for tough casings, frames and handles, and – reinforced with glass – as bearings gears and other load-bearing parts. There are many grades (Nylon 6, Nylon 66, Nylon 11,...) each with slightly different properties.

Design Notes Nylons are tough, strong and have a low coefficient of friction. They have useful properties over a wide range of temperature (–80–120 C). They are easy to injection mold, machine and finish, can be thermally or ultrasonically bonded, or joined with epoxy, phenol-formaldehyde, or polyester adhesives. Certain grades of nylon can be electroplated allowing metallization, and most accept print well. A blend of PPO/nylon is used in fenders, exterior body parts. Nylon fibers are strong, tough, elastic and glossy, easily spun into yarns or blended with other materials. Nylons absorb up to 4% water; to prevent dimensional changes, they must be conditioned before molding, allowing them to establish equilibrium with normal atmospheric humidity. Nylons have poor resistance to strong acids, oxidizing agents and solvents, particularly in transparent grades.

Typical Uses Light duty gears, bushings, sprockets, and bearings; electrical equipment housings, lenses, containers, tanks, tubing, furniture casters, plumbing connections, bicycle wheel covers, ketchup bottles, chairs, toothbrush bristles, handles, bearings, food packaging. Nylons are used as hot-melt adhesives for book bindings; as fibers – ropes, fishing line, carpeting, car upholstery, and stockings; as aramid fibers – cables, ropes, protective clothing, air filtration bags, and electrical insulation.

Competing Materials Polypropylene, polyester, and ABS.

The Environment Nylons have no known toxic effects, although they are not entirely inert biologically. Nylons are oil-derivatives, but this will not disadvantage them in the near future. With refinements in polyolefin catalysis, nylons face stiff competition from less expensive polymers.

Technical Notes The density, stiffness, strength, ductility, and toughness of nylons all lie near the average for unreinforced polymers. Their thermal conductivities and thermal expansion are a little lower than average. Reinforcement with mineral, glass powder, or glass fiber increases the modulus, strength, and density. Semi-crystalline nylon is distinguished by a numeric code for the material class indicating the number of carbon atoms between two nitrogen atoms in the molecular chain. The amorphous material is transparent, the semi-crystalline material is opal white.

Polymethylmethacrylate (PMMA), Acrylic

What Is It? When you think of PMMA, think transparency. Acrylic, or PMMA, is the thermoplastic that most closely resembles glass in transparency and resistance to weathering. The material has a long history: discovered in 1872, commercialized in 1933, its first major application was as cockpit canopies for fighter aircraft during the Second World War.

Design Notes Acrylic, or PMMA, is hard and stiff as polymers go, easy to polish but sensitive to stress concentrations. It shares with glass a certain fragility, something that can be overcome by blending with acrylic rubber to give a high impact alloy (HIPMMA). PVC can be blended with PMMA to give tough, durable sheets. Acrylic is available as a sheet, rod, or tube and can be shaped by casting or extrusion. Cell casting uses plates of glass and gasketing for a mold; it allows clear and colored panels up to 4 inches thick to be cast. Extrusion pushes melted polymer pellets through a die to give a wide variety of shapes, up to 0.25 inches thick for sheet. Clear and colored PMMA sheet lends itself to thermoforming, allowing inexpensive processing. A hybrid sheet manufacturing process, continuous casting, combines the physical benefits of cell casting and the cost efficiency of extrusion. Extruded and continuous cast sheet have better thickness tolerance than cell-cast sheet. PMMA can be joined with epoxy, alpha-cyanoacrylate, polyester, or nitrile-phenolic adhesives. It scratches much more easily than glass, but this can be partially overcome with coatings.

Typical Uses Lenses of all types; cockpit canopies and aircraft windows; signs; domestic baths; packaging; containers; electrical components; drafting equipment; tool handles; safety spectacles; lighting, automotive tail lights, chairs, contact lenses, windows, advertising signs, static dissipation products; compact disks.

Competing Materials Polycarbonate, polystyrene, PVC, PET.

The Environment Acrylics are non-toxic and recyclable.

Technical Notes Polymers are truly transparent only if they are completely amorphous – that is, non-crystalline. The lumpy shape of the PMMA molecule ensures an amorphous structure, and its stability gives good weathering resistance. PMMA is attacked by esters, ketones, acids, and hydro-carbons, and has poor resistance to strong acids or bases, solvents, and acetone.

Attributes of Acrylic

Price, \$/kg	1.70–2.40
Density, Mg/m ³	1.16–1.22

Technical Attributes

El. modulus, GPa	2.24–3.8
Elongation, %	2–10
Fr. toughness, MPa·m ^{1/2}	0.7–1.6
Vickers hardness, H _v	16–21
Yld. strength, MPa	53.8–72.4
Service temp., °C	–50–100
Specific heat, J/kg·K	1485–1606
Th. conduct., W/m·K	0.08–0.25
Th. expansion, 10 ^{–6} /K	72–162

Eco-Attributes

Energy content, MJ/kg	97–105
Carbon footprint, CO ₂ (kg/kg)	6.8
Recycle potential	Low

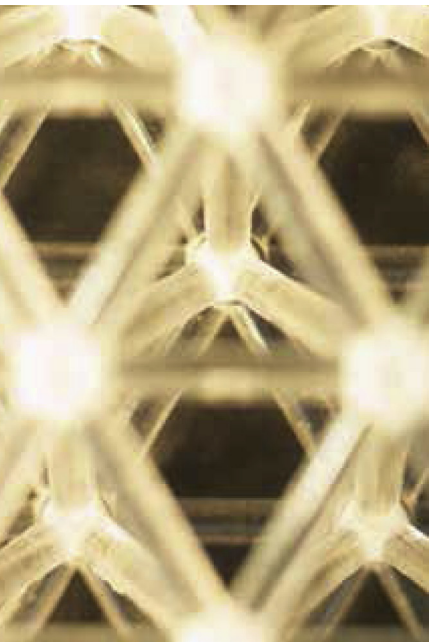
Aesthetic Attributes

Low (o), High Pitch (10)	7
Muffled (o), Ringing (10)	4
Soft (o), Hard (10)	7
Warm (o), Cool (10)	4–5

Features (Relative to Other Polymers)

Optically clear
Easily colored
UV resistant





Attributes of Polycarbonate

Price, \$/kg	3.80–4.30
Density, Mg/m ³	1.14–1.21

Technical Attributes

El. modulus, GPa	2.21–2.44
Elongation, %	70–150
Fr. toughness, MPa·m ^{1/2}	2.1–4.602
Vickers hardness, H _v	17–22
Yld. strength, MPa	59.1–69
Service temp., C	–40–120
Specific heat, J/kg·K	1535–1634
Th. conduct., W/m·K	0.19–0.22
Th. expansion, 10 ^{–6} /K	120.1–136.8

Eco-Attributes

Energy content, MJ/kg	120–130
Carbon footprint, CO ₂ (kg/kg)	6.0
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	7
Muffled (o), Ringing (10)	4
Soft (o), Hard (10)	7
Warm (o), Cool (10)	4–5

Features (Relative to Other Polymers)

Optically clear
Strong
Tough

Polycarbonate (PC)

What Is It? PC is one of the “engineering” thermoplastics, meaning that it has better mechanical properties than the cheaper “commodity” polymers. The family includes the plastics polyamide (PA), polyoxymethylene (POM), and polytetrafluorethylene (PTFE). The benzene ring and the -OCOO- carbonate group combine in pure PC to give it its unique characteristics of optical transparency and good toughness and rigidity, even at relatively high temperatures. These properties make PC a good choice for applications such as compact disks, safety hard hats, and housings for power tools. To enhance the properties of PC even further, it is possible to co-polymerize the molecule with other monomers (improves the flame retardancy, refractive index, and resistance to softening), or to reinforce the PC with glass fibers (giving better mechanical properties at high temperatures).

Design Notes The optical transparency and high impact resistance of PC make it suitable for bullet-resistant or shatter-resistant glass applications. It is readily colored. PC is usually processed by extrusion or thermoforming (techniques that impose constraints on design), although injection molding is possible. When designing for extrusion with PC, the wall thickness should be as uniform as possible to prevent warping, and projections and sharp corners avoided – features like hollows and lone unsupported die sections greatly increase the mold cost. The stiffness of the final part can be improved by the incorporation of corrugations or embossed ribs. PC can be reinforced using glass fibers to reduce shrinkage problems on cooling and to improve the mechanical performance at high temperatures. It can be joined using adhesives, fasteners, or welding.

Typical Uses Compact disks, housings for hairdryers, toasters, printers and power tool housings, refrigerator linings, mechanical gears, instrument panels, motorcycle helmets, automotive bumpers and body parts, riot shields.

Competing Materials Acetal, acrylic, and polyester.

The Environment The processing of engineering thermoplastics requires a higher energy input than that of commodity plastics, but otherwise there are no particular environmental penalties. PC can be recycled if unreinforced.

Technical Notes The combination of the benzene ring and carbonate structures in the PC molecular structure give the polymer its unique characteristics of high strength and outstanding toughness. PC can be blended with ABS or polyurethane. ABS/PC gets its flame retardance and UV resistance from polycarbonate at a lower cost than that of ABS. PU/PC gets its rigidity from polycarbonate and flexibility and ease of coating from polyurethane.

Polyoxymethylene (POM), Acetal

What Is It? POM was first marketed by DuPont in 1959 as Delrin. It is similar to nylon but is stiffer, and has better fatigue and water resistance – nylons, however, have better impact and abrasion resistance. It is rarely used without modifications: most often filled with glass fiber, flame retardant additives or blended with PTFE or PU. The last, POM/PU blend, has good toughness. POM is used where requirements for good moldability, fatigue resistance, and stiffness justify its high price relative to mass polymers, like polyethylene, which are polymerized from cheaper raw materials using lower energy input.

Design Notes POM is easy to mold by blow molding, injection molding, or sheet molding, but shrinkage on cooling limits the minimum recommended wall thickness for injection molding to 0.1 mm. As manufactured, POM is gray but it can be colored. It can be extruded to produce shapes of constant cross-section such as fibers and pipes. The high crystallinity leads to increased shrinkage upon cooling. It must be processed in the temperature range 190–230 C and may require drying before forming because it is hygroscopic. Joining can be done using ultrasonic welding, but POM’s low coefficient of friction requires welding methods that use high energy and long ultrasonic exposure. Adhesive bonding is an alternative. POM is also an electrical insulator. Without co-polymerization or the addition of blocking groups, POM degrades easily.

Typical Uses Automobile carburetors and door handles, videocassette parts, gears and bearings, tool handles, plumbing parts, clothing zips.

Competing Materials Nylon, polyester, PTFE.

The Environment Acetal, like most thermoplastics, is an oil derivative, but this poses no immediate threat to its use.

Technical Notes The repeating unit of POM is $-(CH_2O)_n$, and the resulting molecule is linear and highly crystalline. Consequently, POM is easily moldable, has good fatigue resistance and stiffness, and is water resistant. In its pure form, POM degrades easily by de-polymerization from the ends of the polymer chain by a process called “unzipping.” The addition of “blocking groups” at the ends of the polymer chains or co-polymerization with cyclic ethers such as ethylene oxide prevents unzipping and hence degradation.



Attributes of Acetal

Price, \$/kg	2.70–4.00
Density, mg/m ³	1.39–1.43

Technical Attributes

El. modulus, GPa	2.35–6.27
Elongation, %	10–75
Fr. toughness, MPa·m ^{1/2}	1.71–4.2
Vickers hardness, H _v	14–24
Yld. strength, MPa	48.6–72.4
Service temp., C	–30–110
Specific heat, J/kg·K	1364–1433
Th. conduct., W/m·K	0.22–0.35
Th. expansion, 10 ^{–6} /K	75–200

Eco-Attributes

Energy content, MJ/kg	115–121
Carbon footprint, CO ₂ (kg/kg)	4.0
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	7
Muffled (o), Ringing (1o)	4–5
Soft (o), Hard (1o)	7
Warm (o), Cool (1o)	4–5

Features (Relative to Other Polymers)

Low friction
Wear resistant
Water resistant



Attributes of PTFE

Price, \$/kg	13.90–15.90
Density, Mg/m ³	2.14–2.2

Technical Attributes

El. modulus, GPa	0.4–0.55
Elongation, %	200–400
Fr. toughness, MPa·m ^{1/2}	5–7
Vickers hardness, H _v	59–65
Yld. strength, MPa	19.7–21.7
Service temp., C	–270–250
Specific heat, J/kg·K	1014–1054
Th. conduct., W/m·K	0.24–0.26
Th. expansion, 10 ^{–6} /K	126–216

Eco-Attributes

Energy content, MJ/kg	180–195
Carbon footprint, CO ₂ (kg/kg)	6.0
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	5
Muffled (o), Ringing (10)	2–3
Soft (o), Hard (10)	6
Warm (o), Cool (10)	5
Gloss, %	85–95

Features (Relative to Other Polymers)

Extremely durable
High temperatures
Low friction

Polytetrafluoroethylene (PTFE)

What Is It? PTFE (Teflon) is a member of the fluoroplastic family, which includes chlorotri-fluoroethylene, CTFE or CFE, polyvinyl fluoride, PVF, and polyvinylidene fluoride PVF₂. PTFE has exceptionally low friction, is water repellant, and extremely stable. It was first commercialized in the late 1940s as Teflon. Non-stick cooking utensils (Tefal = teflon coated aluminum) exploit its chemical inertness, its thermal stability, and its non-wettability – the reason nothing sticks to it. It is expensive as polymers go, but it is used in high-value applications (non-stick pans; GoreTex rain gear; artificial arteries).

Design Notes PTFE is 2.7 times denser than polyethylene and 12 times more expensive. But it is much more resistant to chemical attack; it can safely be used from –270 to +250 C. It has remarkably low friction; and it has an exceptional ability to resist wetting. All fluoroplastics are white, and to some degree, translucent. They give long-term resistance to attacks of all sorts, including ultraviolet radiation. PTFE itself has a characteristically soft, waxy feel, partly because of the low coefficient of friction. It is an excellent electrical insulator, with low dielectric loss. It can be “foamed” to give a light, micro-porous film that rejects liquid water but allows water vapor to pass – the principle of GoreTex. The mechanical properties of PTFE are not remarkable, but it can be made more abrasive resistant by filling with inert ceramic, and it can be reinforced with glass, nylon, or Kevlar fibers to give a leather-like skin of exceptional toughness, strength, and weather-resistance (exploited in tensile roofs). Bonding PTFE is difficult; thermal or ultrasonic methods are good; epoxy, nitrile-phenolic, and silicone adhesives can be used.

The use of GoreTex derivatives in fabrics is expanding. The pore size in these fabrics can be controlled to reject not merely water, but bacteria, with potential for protective clothing for surgeons, and against certain kinds of biological weapons.

Typical Uses Wire and cable covers; high-quality insulating tape; corrosion resistant lining for pipes and valves; protective coatings; seals and gaskets; low friction bearings and skis; translucent roofing and weather protection for other polymers (e.g. ABS); non-stick cooking products; water repellent fabrics.

Competing Materials Polyethylene for low friction, PVC for external use for roofs and cladding.

The Environment PTFE is non-flammable and FDA approved. Like all thermoplastics, simple PTFE can be recycled. But in making it into non-stick surfaces, or in transforming it into GoreTex, additives are made which prevent further recycling.

Technical Notes Fluorine is the most reactive of gases, yet combined with carbon to form polytetrafluoroethylene, PTFE, it becomes the most stable of molecules, resistant to practically everything except excessive heat. It has an exceptionally low coefficient of friction against steel, making it attractive for bearings and – in dispersed form – as a lubricant.

Ionomers

What Is It? Ionomers, introduced by DuPont in 1964, are flexible thermoplastics but they have ionic cross-links, from which they derive their name. Their thermoplastic character allows them to be processed by blow molding, injection molding, and thermoforming and to be applied as coatings. But cooled below 40 C they acquire the characteristic of thermo sets: high strength, good adhesion, and chemical stability.

Design Notes Ionomers are very tough, they have high tensile strength and excellent impact, tear, grease, and abrasion resistance. Optical clarity is also quite high. They are most often produced as film. Ionomers have outstanding hot tack (10 times that of LDPE). Their resistance to weather is similar to that of PE, and like PE, they can be stabilized with the addition of carbon black. Permeability is also similar to that of PE, except for carbon dioxide where the permeability is lower. Low temperature flexibility is excellent but they should not be used at temperatures above 70 C. Because of the ionic nature of the molecules, ionomers have good adhesion to metal foil, nylon, and other packaging films. Foil and extrusion coating are common. Ionomers have higher moisture vapor permeability (due to the low crystallinity) than polyethylene, are easily sealed by heat and retain their resilience over a wide temperature range.

Typical Uses Food packaging, athletic soles with metal inserts, ski boots, ice skate shells, wrestling mats, thermal pipe insulation, license plate holders, golf ball covers, automotive bumpers, snack food packaging, blister packs, bottles.

Competing Materials LDPE, polyisoprene.

The Environment Ionomers have properties that resemble thermosets yet they can be recycled – an attractive combination.

Technical Notes Ionomers are co-polymers of ethylene and methacrylic acid. Some grades contain sodium and have superior optical properties and grease resistance; some contain zinc and have better adhesion. The ionic cross-links are stable at room temperature, but break down upon heating above about 40 C. The advantages of cross-linking are seen in the room temperature toughness and stiffness. At high temperatures the advantages of linear thermoplastics appear – ease of processing and recyclability.



Attributes of Ionomers

Price, \$/kg	1.40-1.60
Density, mg/m ³	0.93-0.96

Technical Attributes

El. modulus, GPa	0.2-0.42
Elongation, %	300-700
Fr. toughness, MPa·m ^{1/2}	1.14-3.43
Vickers hardness, H _v	2-5
Yld. strength, MPa	8.27-15.9
Service temp., C	-30-70
Specific heat, J/kg·K	1814-1887
Th. conduct., w/m·K	0.24-0.28
Th. expansion, 10 ⁻⁶ /K	180-306

Eco-Attributes

Energy content, MJ/kg	115-120
Carbon footprint, CO ₂ (kg/kg)	4.2
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	5-6
Muffled (o), Ringing (1o)	2-3
Soft (o), Hard (1o)	6
Warm (o), Cool (1o)	4-5
Gloss, %	20-143

Features (Relative to Other Polymers)

Strong
Tough
Low permeability

Attributes of PU

Price, \$/kg	5.44-6.01
Density, Mg/m ³	1.12-1.24

Technical Attributes

El. modulus, GPa	1.31-2.07
Elongation, %	60-550
Fr. toughness, MPam ^{1/2}	1.84-4.97
Vickers hardness, H _v	16-22
Yld. strength, MPa	40-53.8
Service temp., C	-30-80
Specific heat, J/kg·K	1554-1616
Th. conduct., W/m·K	0.24-0.24
Th. expansion, 10 ⁻⁶ /K	90-144

Eco-Attributes

Energy content, MJ/kg	110-118
Carbon footprint, CO ₂ (kg/kg)	3-7
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	6-7
Muffled (o), Ringing (1o)	3-4
Soft (o), Hard (1o)	7
Warm (o), Cool (1o)	4-5
Gloss, %	100

Features (Relative to Other Polymers)

- Flexible
- Tough
- Durable

Polyurethane (PU)

What Is It? Think of polyurethanes and you think of soft, stretchy, materials, and fabrics (Lycra or Spandex), but they can also be leathery or rigid. Like PVC, polyurethanes have thermoplastic, elastomeric, and thermosetting grades. They are easily foamed; some 40% of all PU is made into foam by mixing it with a blowing agent. The foams can be open- or closed-cell, microcellular, or filter grades. PU is a versatile material.

Design Notes PU foams are cheap, easy to shape, and have good structural performance and resistance to hydrocarbons. Most foamable PUs are thermosets, so they are shaped by casting rather than heat-molding, giving a high surface finish and the potential for intricate shapes. In solid form PUs can be produced as sheet or bulk shapes. For load-bearing applications such as power-transmission belts and conveyor belts tppus are reinforced with nylon or aramid fibers, giving flexibility with high strength. tppus can have a wide range of hardness, softening point, and water absorption. They are processed in the same way as nylon, but are considerably more expensive. tppu fibers are hard, wiry, and have a low softening point compared to nylon; they have been used as bristles on brushes. elpu fibers are much more common – they are used in clothing and flexible products under the trade-name of Spandex or Lycra. elpu foams are used for mattresses, seating of furniture, and packaging; more rigid foams appear as crash protection in cars, and, in low density form (95% gas) as insulation in refrigerators and freezers. These flexible resins are good in laminate systems where damping is required. elpu is amorphous, tppu is crystalline; elpu is commonly cast or drawn, tppu is commonly injection molded or extruded. Polyurethane elastomers have exceptional strength (up to 48 MPa) and abrasion resistance, low compression set, and good fuel resistance. They have useful properties from -55 C to 90 C. PU foam is usually processed by reaction-injection molding: the resin and hardener are mixed and injected into a mold where they react and set. PU can be bonded with polyurethane, nitrile, neoprene, epoxies, and cyanacrylates adhesives. It has good resistance to hydrocarbons, degrades in many solvents, and is slow burning in fire.

Typical Uses Cushioning and seating, packaging, running shoe soles, tires, wheels, fuel hoses, gears, bearings, wheels, car bumpers, adhesives, fabric-coatings for inflatables, transmission belts, diaphragms, coatings that are resistant to dry-cleaning, furniture, thermal insulation in refrigerators and freezers; as elastomers: truck wheels, shoe heels, bumpers, conveyor belts, and metal forming dyes.

Competing Materials Nylon, acetal, natural rubber, polystyrene foams.

The Environment PU is synthesized from diisocyanate and a polyester or polyether. The diisocyanate is toxic, requiring precautions during production. PU itself is inert and non toxic. The flammability of PU foam, and the use of CFCs as blowing agents in the foaming process were, at one time, a cause for concern. New flame retardants now mean that PU foams meet current fire safety standards, and CFCs have been replaced by CO₂ and HFCs which do not have a damaging effect on the ozone layer.

Thermoplastic pus can be recycled (thermosetting pus cannot), and when all useful life is over, incinerated to recover heat. Legislation for return of packaging and disposal problems may disadvantage PU.

Technical Notes Almost all polyurethanes are co-polymers of linked polyester, alcohols, and isocyanate groups. Depending on the mix, polyurethanes can be soft and elastic (Lycra, Spandex) or nearly rigid (track-shoe soles, floor tiles), making PU one of the most versatile of polymers.

Polyvinylchloride (PVC)

What Is It? PVC – Vinyl – is one of the cheapest, most versatile, and – with polyethylene – the most widely used of polymers and epitomizes their multi-faceted character. In its pure form – as a thermoplastic, tPVC – it is rigid, and not very tough; its low price makes it a cost-effective engineering plastic where extremes of service are not encountered. Incorporating plasticizers creates flexible PVC, ePVC, a material with leather-like or rubber-like properties and used a substitute for both. By contrast, reinforcement with glass fibers gives a material that is sufficiently stiff, strong and tough to be used for roofs, flooring, and building panels. Both rigid and flexible PVC can be foamed to give lightweight structural panels, and upholstery for cars and domestic use. Blending with other polymers extends the range of properties further: vinyl gramophone records were made of a vinyl chloride/acetate co polymer; blow molded bottles and film are a vinyl chloride/acrylic co-polymer.

Design Notes In its pure form, PVC is heavy, stiff, and brittle. Plasticizers can transform it from a rigid material to one that is almost as elastic and soft as rubber. Plasticized PVC is used as a cheap substitute for leather, which it can be made to resemble in color and texture. It is less transparent than PMMA or PC, but it also costs much less, so it is widely used for transparent, disposable containers. PVC is available as film, sheet, or tube. It can be joined with polyester, epoxy, or polyurethane adhesives. It has excellent resistance to acids and bases and good barrier properties to atmospheric gases, but poor resistance to some solvents.

Typical Uses tPVC: pipes, fittings, profiles, road signs, cosmetic packaging, canoes, garden hoses, vinyl flooring, windows and cladding, vinyl records, dolls, medical tubes. ePVC: artificial leather, wire insulation, film, sheet, fabric, car upholstery.

Competing Materials Polyethylene and polypropylene, PTFE for high performance roofing.

The Environment The vinyl chloride monomer is thoroughly nasty stuff, leading to pressure to discontinue production. But properly controlled, the processing is safe, and the polymer PVC has no known harmful effects. Disposal, however, can be a problem: thermal degradation releases chlorine, HCl, and other toxic compounds, requiring special high temperature incineration for safety.

Technical Notes PVC can be a thermoplastic or a thermoset. There are many types of PVC: expanded rigid PVC, type I, type II, CPVC, acrylic/PVC blend, clear PVC.



Attributes of PVC

Price, \$/kg	1.00–1.20
Density, mg/m ³	1.3–1.58

Technical Attributes

El. modulus, GPa	2.14–4.14
Elongation, %	11.93–80
Fr. toughness, MPam ^{1/2}	1.46–5.12
Vickers hardness, H _v	10–15
Yld. strength, MPa	35.4–52.1
Service temp., °C	–20–70
Specific heat, J/kg·K	1355–1445
Th. conduct., W/m·K	0.15–0.29
Th. expansion, 10 ^{–6} /K	1.8–180

Eco-Attributes

Energy content, MJ/kg	77–83
Carbon footprint, CO ₂ (kg/kg)	2.5
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	6–7
Muffled (o), Ringing (1o)	4
Soft (o), Hard (1o)	7
Warm (o), Cool (1o)	4–5

Features (Relative to Other Polymers)

Corrosion resistant
Low cost
Resilient



Attributes of Polyester

Price, \$/kg	1.25-2.5
Density, Mg/m ³	1.19-1.81

Technical Attributes

El. modulus, GPa	1.6-4.4
Elongation, %	1-3-5
Fr. toughness, MPam ^{1/2}	1.05-9.16
Vickers hardness, H _v	11-40
Yld. strength, MPa	30-40
Service temp., C	-20-160
Specific heat, J/kg·K	1160-1587
Th. conduct., W/m·K	0.28-0.58
Th. expansion, 10 ⁻⁶ /K	115-170

Eco-Attributes

Energy content, MJ/kg	89-95
Carbon footprint, CO ₂ (kg/kg)	3.0
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	6-8
Muffled (o), Ringing (10)	4-6
Soft (o), Hard (10)	7-8
Warm (o), Cool (10)	4-5

Features (Relative to Other Polymers)

- Versatility
- Cheap
- Strong and tough

Polyesters (PET, PBT, PETg)

What Is It? The name polyester derives from a combination of “Polymerization” and “esterification.” Saturated polyesters are thermoplastic – examples are PET, PBT, PETg; they have good mechanical properties to temperatures as high as 160 C. PET is crystal-clear, impervious to water and CO₂, but a little oxygen does get through. It is tough, strong, easy to shape, join, and sterilize – allowing reuse. When its first life comes to an end, it can be recycled to give fibers and fleece materials for clothing and carpets. Unsaturated polyesters are thermosets; they are used as the matrix material in glass fiber/polyester composites. Polyester elastomers are resilient and stretch up to 45% in length; they have good fatigue resistance and retain flexibility at low temperatures.

Design Notes There are four grades of thermoplastic polyesters: unmodified, flame retardant, glass-fiber reinforced, and mineral-filled. Unmodified grades have high elongation; flame retardant grades are self-extinguishing; glass-fiber reinforced grades (like Rynite) are some of the toughest polymers but there are problems with dimensional stability; and mineral-filled grades are used to counter warping and shrinkage although some strength is lost. The PET used in carbonated drink containers is able to withstand pressure from within, it is recyclable and lighter than glass. The permeability to oxygen is overcome by sandwiching a layer of polyethylvinylidene-alcohol between two layers of PET giving a multi-layer material that can still be blow molded. Polyester can be optically transparent, clear, translucent, white, or opaque; the resin is easily colored.

Thermosetting polyesters are the cheapest resins for making glass or carbon fiber composites, but they have lower strength than epoxies. They can be formulated to cure at or above room temperature. Modifications can improve the chemical resistance, UV resistance, and heat resistance without too much change in the ease of processing. Polyester elastomers have relatively high moduli and are stronger than polyurethanes. They have good melt flow properties, low shrinkage, good resistance to oils and fuels. Polyester can be made conductive by adding 30% carbon fiber. As a tape, Mylar is used for magnetic sound recording. Unfilled polyester thermosetting resins are normally used as surface coatings but they tend to be brittle. A warning: thermosetting polyester corrodes copper.

Typical Uses Decorative film, metallized balloons, photography tape, videotape, carbonated drink containers, oven-proof cookware, windsurfing sails, credit cards, carpets, clothing, brushes, boats, fishing rods, automobile body panels.

Competing Materials Glass, acrylic, polystyrene, polycarbonate.

The Environment PET bottles take less energy to make than glass bottles of the same volume, and they are much lighter – saving fuel in delivery. Thick-walled bottles can be reused; thin-walled bottles can be recycled – and are, particularly in the US.

Technical Notes Polyesters are made by a condensation reaction of an alcohol like ethyl alcohol (the one in beer) and an organic acid like acetic acid (the one in vinegar). The two react, releasing water, and forming an ester. PET, PBT, and PCT are not cross-linked and thus are thermoplastic. The polyesters that are used as the matrix polymer in bulk and sheet molding compounds are thermosets.

Silicone

What Is It? Silicones are high performance, high cost materials. They have poor strength, but can be used over an exceptional range of temperature (−100–300 C), have great chemical stability, and an unusual combination of properties (Silly Putty is a silicone elastomer – it bounces when dropped but flows if simply left on the desk.).

Design Notes Silicones are the most chemically stable of all elastomers, with good electrical properties but relatively low strength (up to 5 MPa). Silicone resins are expensive and they are difficult to process. They have properties like those of natural rubber, but have a completely different chemical structure. Glass fibers and other fillers are commonly used as reinforcement. The resulting parts are relatively low in strength but have high heat resistance. For glass fiber composites, the mechanical properties are better with a phenolic or melamine resin, but the electrical properties are better with silicone. Electrical and high temperature applications dominate their use. They are chemically inert, do not absorb water and can be used in surgical or food-processing equipment and seals. Silicones can be produced as fluids, adhesives, coatings, elastomers, molding resins, and release agents. But each suffers from a short shelf life (3–6 months). Silicone fluids were the earliest commercial silicones, used as lubricants over a wide range of temperature (−75–450 C). Silicone adhesives can be made as liquids or pastes.

RTV silicone was first developed for its rapid mold filling – a few seconds at high temperatures. Silicone elastomers can be air-curing, cold-curing (by the addition of a catalyst), or heat-curing; they may be pure or loaded with carbon black to give conductivity. Silicone molding resins are compounded with inert fillers to allow the production of flexible parts with high heat resistance.

Typical Uses Wire and cable insulation, mold release agents, lens cleaning tissue coatings, seals, gaskets, adhesives, o-rings, insulation, encapsulation, and potting of electronic circuitry, surgical and food-processing equipment, baby bottle tips, breast implants, swimming caps, and seals for swimming goggles.

Competing Materials Polyurethanes, EVA.

The Environment Silicones are energy-intensive – although they are not oil-derivatives. They cannot be recycled.

Technical Notes Silicone and fluoro-silicone elastomers have long chains of linked O-Si-O-Si- groups (replacing the -C-C-C-C- chains in carbon-based elastomers), with methyl (CH₃) or fluorine (F) side chains. Some are relatively stiff solids, others are elastomers.



Attributes of Silicone

Price, \$/kg	7.20–17.20
Density, mg/m ³	1.1–2.3

Technical Attributes

El. modulus, GPa	0.001–0.05
Elongation, %	0.8–5.3
Fr. toughness, MPa·m ^{1/2}	0.03–0.7
Yld. strength, MPa	2.4–5.5
Service temp., C	−100–300
Specific heat, J/kg·K	1050–1300
Th. conduct., W/m·K	0.2–2.55
Th. expansion, 10 ^{−6} /K	250–300

Eco-Attributes

Energy content, MJ/kg	175–190
Carbon footprint, CO ₂ (kg/kg)	7.9
Recycle potential	Low

Aesthetic Attributes

Low (o), High Pitch (1o)	1–4
Muffled (o), Ringing (1o)	0–1
Soft (o), Hard (1o)	3–4
Warm (o), Cool (1o)	4–6

Features (Relative to Other Polymers)

Extremes of temperature
Durable
Low friction



Attributes of Phenolic

Price, \$/kg	0.90–1.20
Density, Mg/m ³	1.24–1.32

Technical Attributes

El. modulus, GPa	2.76–4.83
Elongation, %	1.5–2
Fr. toughness, MPa·m ^{1/2}	0.79–1.21
Vickers hardness, H _v	8–15
Yld. strength, MPa	27.6–49.68
Service temp., °C	–20–160
Specific heat, J/kg·K	1467–1526
Th. conduct., W/m·K	0.141–0.152
Th. expansion, 10 ^{–6} /K	120.1–124.9

Eco-Attributes

Energy content, MJ/kg	94–100
Carbon footprint, CO ₂ (kg/kg)	3.6
Recycle potential	Low

Aesthetic Attributes

Low (o), High Pitch (1o)	7
Muffled (o), Ringing (1o)	4
Soft (o), Hard (1o)	7
Warm (o), Cool (1o)	4

Features (Relative to Other Polymers)

- Flame retardant
- Durable
- Strong and tough

Phenolic

What Is It? Bakelite, commercialized in 1909, triggered a revolution in product design. It was stiff, fairly strong, could, to a muted degree, be colored, and – above all – was easy to mold. Products that, earlier, were hand-crafted from woods, metals, or exotics such as ivory, could now be molded quickly and cheaply. At one time the production of phenolics exceeded that of PE, PS, and PVC combined. Now, although the ratio has changed, phenolics still have a unique role. They are stiff, chemically stable, have good electrical properties, are fire-resistant and easy to mold – and they are cheap.

Design Notes Phenolic resins are hard, tolerate heat, and resist most chemicals except the strong alkalis. Phenolic laminates with paper have excellent electrical and mechanical properties and are cheap; filled with cotton the mechanical strength is increased and a machined surface is finer; filled with glass the mechanical strength increases again and there is improved chemical resistance. Fillers play three roles: extenders (such as wood flour and mica) are inexpensive and reduce cost; functional fillers add stiffness, impact resistance and limit shrinkage; reinforcements (such as glass, graphite and polymer fibers) increase strength, but cost increases too. Unfilled phenolics are susceptible to shrinkage when exposed to heat over time, glass-filled resins are less susceptible. They have good creep resistance, and they self-extinguish in a fire.

Phenolics can be cast (household light and switch fittings) and are available as rod and sheet. Impregnated into paper (Nomex) and cloth (Tufnol), they have exceptional durability, chemical resistance and bearing properties. Phenolics accept paint, electroplating, and melamine overlays.

Typical Uses Switchboards, insulating washers, intricate punched parts (phenolic with paper laminate), gears, pinions, bearings, bushings (phenolic with cotton laminate), gas-kets and seals (phenolic with glass), used to bond friction materials for automotive brake linings, beads, knife handles, paperweights, billiard balls, domestic plugs and switches, telephones, fuse box covers, distributor heads, saucepan handles and knobs, golf ball heads for typewriters, toilet seats. As a foam, phenolic resin is used in paneling for building work; its fine resistance is a particular attraction.

Competing Materials Epoxy, polyester, silicone.

The Environment Phenolics, like all thermosets, cannot be recycled.

Technical Notes Phenolic resins are formed by a condensation, generating water in the process, involving a reaction between phenol and formaldehyde to form the A-stage resin. Fillers, colorants, lubricants, and chemicals to cause cross-linking are added to form the B-stage resin. This resin is then fused under heat and pressure converting to the final product – a C-stage resin – or completely cross-linked polymer.

Cellulose Acetate (CA)

What Is It? Cellulose is starch; it is one of the main structural polymers in plants (specifically that of wood or cotton). These natural fibers are treated with acids to produce a resin, a process called “esterification.” Cellulose acetate (CA), cellulose acetate butyrate (CAB) and cellulose acetate propionate (CAP) are three common cellulose materials. CA combines toughness, transparency, and a natural surface texture. Some cellulose resins are biodegradable allowing their use for envelopes with transparent windows that can be disposed of as if they were paper alone.

Design Notes Cellulose materials have good optical transparency (up to 90%) and mechanical properties; they are often used in products where surface finish is important. They can be translucent, transparent, or opaque, and come in a range of colors including pearlescent, opaque, and metallic. Cellulose materials are antistatic and so dust does not stick to the surface. They have glossy surfaces and a self-polishing effect that allows surface scratches to disappear with use. They can be formulated for outdoor use. Cellulose acetates have a high vapor permeability and limited heat resistance; their electrical insulation and dimensional stability are poor; water absorption is high compared with PVC. Compared with CA, CAB, and CAP are slightly softer, of lower densities and heat distortion temperatures and they flow more easily. CAB and CAP have a wider operating temperature range (0–60 C). In bulk, cellulose acetate often has a light yellow-brown color but it can also attain water white transparency. Cellulose is easily made into fibers, fabrics, and films, known under the trade name of Rayon. It has excellent flow properties and so is well-suited to injection molding but the resin must be kept dry. Stiffer flow grades are available for extrusion to produce film and sheet. These polymers are also some of the best for cutting, turning, and milling. CAB is well-suited for thermoforming.

Typical Uses Film packaging, sunglasses, safety glasses, eye glass frames, laminated brochures, tool handles, hammer heads, electric screwdrivers, photographic film, typewriter keys, blister packaging, combs, hair decoration.

Competing Materials Acrylics, polyethylene, polycarbonate.

The Environment Cellulose – a natural, renewable material – forms one ingredient in cellulose-based polymers. The processing, however, involves chemicals that create a problem of disposal. Most cellulose-based polymers burn easily, requiring protection from naked flame. Some are biodegradable.

Technical Notes Grades of cellulose materials are varied by increasing the level of acid-treatment or by adding plasticizers. Increasing the plasticizer increases flow and toughness but reduces the creep resistance. But this lack of creep resistance can be used to an advantage in molding where parts can be cooled quickly because the stresses will relax quite quickly.



Attributes of Cellulose Acetate

Price, \$/kg	3.40–3.90
Density, mg/m ³	0.98–1.4

Technical Attributes

El. modulus, GPa	0.75–4.1
Elongation, %	5–100
Fr. toughness, MPa·m ^{1/2}	0.85–3.20
Vickers hardness, H _v	18–15
Yld. strength, MPa	24.8–52.4
Service temp., C	–10–60
Specific heat, J/kg·K	1386–1665
Th. conduct., w/m·K	0.13–0.34
Th. expansion, 10 ^{–6} /K	118.8–360

Eco-Attributes

Energy content, MJ/kg	120–126
Carbon footprint, CO ₂ (kg/kg)	3.8
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	6–7
Muffled (o), Ringing (1o)	3–4
Soft (o), Hard (1o)	6–7
Warm (o), Cool (1o)	4–5

Features (Relative to Other Polymers)

Bio-polymer
Transparent
Tough



Attributes of Cellulose Nitrate

Price, \$/kg	3.60-4.20
Density, Mg/m³	1.35-1.4

Technical Attributes

El. modulus, GPa	1.3-1.5
Elongation, %	40-45
Fr. toughness, MPa·m ^{1/2}	1.4-3.2
Vickers hardness, H _v	11-13
Yld. strength, MPa	38-44
Service temp., °C	58-71
Specific heat, J/kg·K	1390-1410
Th. conduct., W/m·K	0.22-0.24
Th. expansion, 10 ⁻⁶ /K	144-216

Eco-Attributes

Energy content, MJ/kg	117-130
Carbon footprint, CO ₂ (kg/kg)	N/A
Recycle potential	High

Features (Relative to Other Polymers)

- Bio-polymer
- Transparent or colored
- Stiff, but flammable

Cellulose Nitrate (Celluloid)

What Is It? Celluloid is generally regarded as the first thermoplastic, dating from 1856 (Parkesine). Its commercial importance is now low and there are few remaining suppliers. Until the 1940s, it was material of choice for 35 mm cine film. Its strengths are transparency with a balance of rigidity and toughness, but its limitation are its exceptional flammability and propensity to thermal decomposition.

Design Notes Celluloid was popular in the early part of the 20th century but its extreme flammability now limits its use in design. Tradenames: Parkesine, Xylonite, Celluloid.

Typical Uses Film, casings for pens, spectacle frames; blister packaging; window envelopes, tool handles; goggles; bathroom fittings; drawing aids; table tennis balls; knife handles; guitar picks, billiard balls.

Competing Materials Acrylic, Polystyrene (PS), cellulose acetate (CA).

The Environment Cellulose nitrate is derived from cellulose, the most plentiful of all natural materials.

Technical Notes Nitro-cellulose is made by treating cotton or paper with strong nitric and sulfuric acid. A typical formulation of celluloid might contain 70-80 parts nitrocellulose, 30 parts camphor, 0-14 parts dye, 1-5 parts ethyl alcohol plus stabilizers, and other agents to increase stability and reduce flammability.

Polyhydroxyalkanoates (PHA, PHB)

What Is It? Polyhydroxyalkanoates (PHAs) are linear polyesters produced in nature by bacterial fermentation of sugar or lipids derived from soybean oil, corn oil, or palm oil. They are fully biodegradable. More than 100 different monomers can be combined within this family to give materials with a wide range of properties, from stiff and brittle thermoplastics to flexible elastomers. The most common type of PHA is PHB (poly-3-hydroxybutyrate) with properties similar to those of PP, though it is stiffer and more brittle. A copolymer of PHB, polyhydroxybutyrate-valerate (PBV) is less stiff and tougher. It is commonly used as a packaging material.

Design Notes The physical properties of PHA biopolymers resemble those of synthetic plastics. Their biodegradability makes them an attractive alternative, meeting the growing problems of pollution by plastic waste. PHB is insoluble in water, and has good oxygen permeability and UV resistance. It is soluble in chloroform and other chlorinated hydrocarbons, which can be used to bond it. It is non-toxic and biocompatible. It can be blow-molded, injection molded, thermoformed, or extruded; it is also available as sheet or film. The drawback of PHAs is their relatively high costs, making them substantially more expensive than synthetic plastic. Tradenames: Mirel.

Typical Uses Packaging, containers, bottles, agricultural mulch film, compost bags, consumer disposables, water treatment.

Competing Materials Polylactic acid (PLA), cellulose-based polymers.

The Environment PHA and PHB are derived from renewable sources and will biodegrade in home composting systems and industrial composting facilities at the end of their useful life.

Technical Notes Polyhydroxyalkanoates (PHAs) are a family of polyesters produced in bacteria as a carbon and energy reserve. Bacterial PHAs are classified into two groups according to the number of carbon atoms in the monomer units: short-chain-length (SCL) PHAs consist of 3–5 carbon chains, and medium-chain-length (MCL) PHAs consist of 6–14 carbon chains. The physical properties of PHAs are dependent upon their monomer units. The most commonly used PHA is Poly-3-hydroxybutyrate (PHB).



Attributes of PHA

Price, \$/kg	5–6
Density, mg/m ³	1.23–1.25

Technical Attributes

El. modulus, GPa	0.8–4
Elongation, %	6–25
Fr. toughness, MPa·m ^{1/2}	0.7–1.2
Vickers hardness, H _v	11–13
Yield strength, MPa	35–40
Service temp., °C	120
Specific heat, J/kg·K	1400–1600
Th. conduct., W/m·K	0.13–0.23
Th. expansion, 10 ^{–6} /K	180–240

Eco-Attributes

Energy content, MJ/kg	50–59
Carbon footprint, CO ₂ (kg/kg)	4.4
Recycle potential	High

Features (Relative to Other Polymers)

Bio-degradable
High Temperatures
Flexible

Polylactide (PLA)

What Is It? Polylactide, PLA, is a biodegradable thermoplastic derived from natural lactic acid from corn, maize, or milk. It resembles clear polystyrene, provides good aesthetics (gloss and clarity), but it is stiff and brittle. The polymer can be compounded to provide a wider range of material properties. It can be processed like most thermoplastics into fibers, films, thermoformed, or injection molded.

Design Notes PLA is a biopolymer that can be molded, thermoformed, and extruded, much like any other thermoplastic. It is transparent and has FDA approval for food packaging. PLA film and sheet can be printed and laminated. Biopolymers are, however, expensive, costing two times as much as commodity plastics like polypropylene. Tradenames: Natureworks Ingeo

Typical Uses Food packaging, plastic bags, plant pots, diapers, bottles, cold drink cups, sheet, and film.

Competing Materials Polyhydroxyalkanoates (PHA, PHB), cellulose-based polymers.

The Environment PLA is derived from renewable sources and, at end of life, can be re cycled, but it is most often successful in situations where industrial composting can be an option for end of life.

Technical Notes PLA is a thermoplastic derived primarily from annually renewable resources (maize, corn, or milk). A bacteria is used to get the lactic acid from these starches and then that material is polymerized to make PLA. It is available in a number of grades, designed for ease of processing. In-line drying may be needed to reduce water content for extrusion and molding. The recommended molding temperature is 165–170 C.

Attributes of PLA

Price, \$/kg	3.0–3.6
Density, Mg/m ³	1.21–1.24

Technical Attributes

El. modulus, GPa	3.45–3.8
Elongation, %	5–7
Fr. toughness, MPa·m ^{1/2}	0.7–1.1
Vickers hardness, H _v	14–18
Yield strength, MPa	48–69
Service temp., C	70–80
Specific heat, J/kg·K	1180–1210
Th. conduct., W/m·K	0.12–0.15
Th. expansion, 10 ^{–6} /K	126–145

Eco-Attributes

Energy content, MJ/kg	52–54
Carbon footprint, CO ₂ (kg/kg)	3.6
Recycle potential	High

Features Relative to Other Polymers.

Bio-degradable
Transparent
Stiff

Thermoplastic Starch (TPS)

What Is It? Starch is a naturally occurring polysaccharide made up of glucose molecules. Its molecular chains are shorter than those of cellulose and the bonds between the sugar molecule building blocks are different. Starch is therefore a polymer, but the problem with using it for making structural products is that it is softened by and dissolves in water. Mater-Bi is a family of biodegradable thermoplastics materials made from maize starch. They are water resistant and resembles polymers made from petrochemicals. They retain their properties while in use, but when composted in an environment containing bacteria, they biodegrade to carbon dioxide, water, and fibrous residue.

Design Notes Mater-Bi can be used in most established plastics processing operations including the manufacture of films and foam, injection molding, and thermoforming. Bottles and containers made from Mater-Bi are safe for many food applications, including oils or oily food, but over a long period of time the material is slightly permeable to water. It has been developed to have properties comparable to plastics such as polystyrene, polyethylene, and polyurethane. The Mater-Bi range of polysaccharides can be extruded, injection molded, thermoformed, and foamed.

Typical Uses Thermo-formed: trays for fresh food packaging, especially fruit and vegetables. Film extrusion: shopping bags, bubble film for wrapping, plastic laminates for paper cups and plates, bags for rubbish disposal, lining for baby nappies, mulching films for horticulture, wrapping for fruit, vegetables, and sanitary products.

Competing Materials PLA, Polyethylene.

The Environment The materials achieve 90% degradation in 50–120 days under normal aerobic composting conditions, decomposing to compost that is used for soil improvement for farming and growing. They have been accepted for certification as biodegraded compost under European Standard EN13432.

Technical Notes Mater-Bi is a biopolymer made from maize starch using additives to create macromolecules. The process uses the amylose component of the starch that is converted chemically to a less granular or crystalline form. This is then reacted chemically by a process called complexing with natural or synthetic complexing agents that promote bond formation between the starch molecule chains.



Attributes of TPS

Price, \$/kg	5.10–6.00
Density, mg/m ³	1.26–1.28

Technical Attributes

El. modulus, GPa	0.24–1.50
Elongation, %	10–80
Fr. toughness, MPa·m ^{1/2}	0.8–1.3
Vickers hardness, H _v	4–6
Yield strength, MPa	16–22
Service temp., °C	60–80
Specific heat, J/kg·K	1500–1700
Th. conduct., W/m·K	0.13–0.23
Th. expansion, 10 ⁻⁶ /K	180–240

Eco-Attributes

Energy content, MJ/kg	24–26
Carbon footprint, CO ₂ (kg/kg)	N/A
Recycle potential	High

Features Relative to Other Polymers.

Biodegradable
Transparent
Stiff

Elastomers

Natural Rubber

Natural rubber was known to the natives of Peru many centuries ago, and is now one of Malaysia's main exports. It made the fortune of Giles Macintosh who, in 1825, devised the rubber-coated waterproof coat that still bears his name. Latex, the sap of the rubber tree, is cross-linked (vulcanized) by heating with sulfur; the amount of the cross-linking determines the properties. It is the most widely used of all elastomers – more than 50% of all produced.

Design Notes Natural rubber is an excellent, cheap, general purpose elastomer with large stretch capacity and useful properties from -50°C to 115°C , but with poor oil, oxidation, ozone, and UV resistance. It has low hysteresis – and is thus very bouncy.

Typical Uses Tires, springs, seals, shock-mounts, and toys.

Styrene-Butadiene Elastomers (SBS, SEBS, SBR, BUNA-S)

Styrene-butadiene elastomers are co-polymers of butadiene and styrene. They exceed all other synthetic rubbers in use-volume.

Design Notes Styrene-butadiene elastomers have low cost, with properties like natural rubber, though lower in strength, thus often requiring reinforcement.

Typical Uses Predominantly tires, hoses, and seals.

Butyl Rubbers (NR)

Butyl rubbers are synthetics that resemble natural rubber in properties.

Design Notes Butyl rubbers have good resistance to abrasion, tearing, and flexing, with exceptionally low gas permeability and useful properties up to 150°C . They have low dielectric constant and loss, making them attractive for electrical applications.

Typical Uses Inner tubes, belts, hoses, cable insulation, encapsulation.

Isoprene

Isoprene is synthetic natural rubber, and is processed in the same way as butyl rubber.

Design Notes Isoprene has low hysteresis and high tear resistance, making it bouncy and tough.

Typical Uses The same as butyl rubber.

Acrylate Elastomers

Acrylate elastomers are made from butyl or ethyl acetate.

Design Notes Acrylate elastomers have good oil resistance but low strength and tear resistance; they have useful properties up to 200°C .

Typical Uses Automobile transmission seals, gaskets, o-rings.

Elastomers, continued

Nitrile Elastomers (NBR, BUNA-N)

Nitrile elastomers are co-polymers of acrylonitrile and butadiene.

Design Notes Nitrile elastomers have excellent resistance to oil and fuels, and retain good flexibility both at low (-30°C) and elevated temperatures.

Typical Uses Oil-well parts, automobile and aircraft fuel hoses, flexible couplings, printing blankets, rollers, pump diaphragms.

Polybutadiene Elastomers

Polybutadiene elastomers have exceptional low temperature performance.

Design Notes Polybutadiene has exceptional resilience and abrasion resistance, retained to -70°C , but with poor chemical resistance.

Typical Uses Generally blended with other polymers to improve low temperature performance; cores for solid golf balls.

Polysulphide Elastomers

Polysulphide elastomers have the highest resistance to oil and gasoline.

Design Notes Polysulphides have excellent chemical and ageing resistance, low gas permeability, though with poor strength.

Typical Uses Oil and fuel hoses, gaskets, washers, diaphragms, sealing and caulking, and adhesives.

Ethylene-Propylene Elastomers (EP, EPM, EPDM)

Ethylene-propylene elastomers are co-polymers of the two monomers that make up their name.

Design Notes Ethylene-propylene elastomers have good resilience, minimal compression-set and good resistance to chemicals, weathering, and uv. Useful properties up to 177°C .

Typical Uses Electrical insulation, footwear, belts, hoses.

Elastomers, continued

Ethylene-Vinyl-Acetate Elastomers (EVA)

Ethylene-vinyl-acetate elastomers are built around polyethylene. They are soft, flexible, and tough, and retain these properties down to -60°C . Fillers improve both hardness and stiffness, but with some degradation of other properties. EVAs blend well with PE because of their chemical similarity.

Design Notes EVA is available in pastel or deep hues, it has good clarity and gloss. It has good barrier properties, little, or no odor, has UV resistance and is FDA-approved for direct food contact. The toughness and flexibility are retained even at low temperatures and it has good stress-crack resistance and good chemical resistance. EVA can be processed by most normal thermoplastic processes: co-extrusion for films, blow molding, rotational molding, injection molding, and transfer molding.

Typical Uses Medical tubes, milk packaging, beer dispensing equipment, bags, shrink film, deep freeze bags, co-extruded and laminated film, closures, ice trays, gaskets, gloves, cable insulation, inflatable parts, running shoes.

Chlorinated Elastomers (Hypalon, Neoprene)

Chlorinated hydrocarbon and chlorinated polyethylene are the leading non-tire elastomers.

Design Notes Chlorinated hydrocarbons are characterized by exceptional chemical resistance, ability to be colored, and useful properties up to 175°C . Some have low gas permeability and low hysteresis, minimizing heating when cyclically loaded, and resist burning.

Typical Uses Tank linings, conveyor and timing belts, shoe soles, o-rings, seals and gaskets, cable jackets, vibration control mounts, diaphragms, tracked vehicle pads, under-hood hoses and tubing, footwear, wetsuits.

Fluoro-Carbon Elastomers (Viton, Fluorel, Kalres, and Perfluoro)

Fluoro-carbon elastomers are based on polyolefins with some of the hydrogen atoms replaced by fluorine. They are heavier than simple hydro-carbons, but much more resistant to heat and chemicals.

Design Notes Fluoro-carbon elastomers have exceptional resistance to chemicals, oxidation, solvents and heat – but they are also expensive. They have useful properties up to 250°C , but become brittle below -20°C and have only modest strengths.

Typical Uses Brake seals, diaphragms, hoses and o-rings.

Thermoplastic Elastomers (TPE)

Thermoplastic elastomers are exceptional in that they can be molded and extruded in standard polymer processing equipment, their scrap can be remelted, and products made from them can be recycled. They include styrene co-polymers (Kraton), polyurethanes (Hytrol, Ritefox, Ecdel), and polypropylene blended with elastomers (Santoprene, Geolast).

Design Notes TPES allow rapid processing by standard thermoplastic methods, and recyclability.

Typical Uses Bumpers, sports shoes, hoses, diaphragms, rollers, seals for automotive, and architectural use.

Elastomers, continued

Attributes of Selected Elastomers

	EVA	Polychloroprene	SBS
Price, \$/kg	1.15–1.29	1.4–4.29	2.50–2.70
Density, Mg/m ³	0.93–0.96	1.23–1.25	0.94–0.95

Technical Attributes

El. modulus, GPa	0.007–0.09	0.001–0.02	.002–0.01
Elongation, %	730–900	100–800	450–500
Fr. toughness, MPa·m ^{1/2}	0.1–0.7	0.1–0.3	0.1–0.3
Yld. strength, MPa	9.5–19	3.4–24	12–21
Service temp., C	–20–60	–50–110	–50–120
Specific heat, J/kg·K	1900–2200	2000–2200	2000–2200
Th. conduct., W/m·K	0.3–0.4	0.1–0.12	0.14–1.49
Th. expansion, 10 ^{–6} /K	160–190	605–625	660–675

Eco-Attributes

Energy content, MJ/kg	95–101	115–124	105–111
Carbon footprint, CO ₂ (kg/kg)	2.1	1.7	4.0
Recycle potential	Low	Low	Low

Aesthetic Attributes

Low (o), High Pitch (10)	3–5	1–2	2–3
Muffled (o), Ringing (10)	1–2	0–1	0–1
Soft (o), Hard (10)	4	3	3–4
Warm (o), Cool (10)	5	4	4–6
Gloss, %	17–123		
Transparent?	No	No	Yes
Translucent?	No	No	Yes
Opaque?	Yes	Yes	Yes

Features (Relative to Other Polymers)

Flexible	Resilient	Translucent
Good barrier properties	Tear resistant	Easily colored
Can be recycled	Chemical resistant	Low cost

Polymer Foams

What Are They? Solid materials are much too solid for comfort and safety. If you want to relax in cushioned luxury and avoid self-inflicted injury when you bump into things, then surround yourself with foams. Foams are made by the controlled expansion and solidification of a liquid or melt through a blowing agent; physical, chemical, or mechanical blowing agents are possible. The resulting cellular material has a lower density, stiffness, and strength than the parent material, by an amount that depends on its relative density – the volume-fraction of solid in the foam. Foams can be soft and flexible, but they can also be hard and stiff. Open-celled foams absorb fluids and can be used as filters; closed cell foams give buoyancy. Self-skinning foams, called “structural” or “syntactic,” have a dense surface skin made by foaming in a cold mold.

Design Notes Polymer foams have characteristics that suit them for cushioning, energy management, acoustic control or thermal insulation. For cushioning, the requirements are comfort and long life; polyurethane foams have been commonly used, but concerns about flammability and durability limit their use in furniture. Energy management and packaging requires the ability to absorb energy at a constant, controlled crushing stress; here polyurethane, polypropylene, and polystyrene foams are used. Acoustic control requires the ability to absorb sound and damp vibration; polyurethane, polystyrene, and polyethylene foams are all used. Thermal insulation requires long life; polyurethane foams were common but are now replaced by phenolics and polystyrenes. When fire-protection is needed phenolic foams are used.

Microcellular elastomeric foams with a small cell size and integral skin are used for shock and vibration control. Examples are expanded EVA and PVC, widely used in shoes. Foamed extrusions have less design restrictions than solid profiles because shrinkage is negligible. The swirled pattern on the surfaces of self-skinning foamed parts, caused by the foaming action, is eliminated by the use of high pressure or by painting.

Structural foam components have high stiffness-to-weight ratios, good sound absorption, high impact strength but poor tensile strength. Stiffening ribs, bosses-and handles can be included in parts without causing molding problems. Reinforcement with glass fibers is possible and improves the structural performance but the ease of molding is diminished.

Polymers can be foamed in place, injection molded, extruded, thermo-formed, laminated, or cast. Low and high pressure injection molding uses pellets of thermoplastic material to which a blowing agent is added. Reaction-injection molding is used with thermosetting polymers, usually polyurethane. Casting of foams, particularly urethanes, uses cheap silicone rubber or epoxy molds, making low volume production practical. Polyurethanes, epoxies, phenolics, and polyesters can all be cast and reaction-injection molded. Foaming reduces material usage and increases bending stiffness without increasing weight.

Polyethylene foam is light, has negligible water absorption and can be used as sheet or film; it is used in thermal and wire insulation and high quality packaging. Polystyrene foam, much used in packaging, is processed by expanded foam molding, extrusion, injection molding, compression molding, blow molding, or thermoforming. Polyurethane, the most widely used elastomer foams, is self-skinning; but it does not age well, cannot be recycled and is no friend of the environment. Developments in polyurethane foam technology, like those of ICI Waterlily, overcome these weaknesses. The most common structural foams are based on ABS, polystyrene, PVC, polyurethane, polyethylene, and phenolic.

Typical Uses Rigid foams: Computer housings, pallets, battery cases, chair frames, TV cabinets, oars, dishwasher tubs, automotive fenders, luggage, cheap boats and recreational vehicle bodies, floatation, filtration, thermal insulation. Flexible foams: cushions, packaging, padding, seating.

Polymer foams, continued

Attributes of Polymer Foams

	Flexible foams	Rigid foams
Price, \$/kg	1-9	2-50
Density, Mg/m ³	0.03-0.1	0.07-0.5

Technical Attributes

El. modulus, GPa	0.0001-0.01	0.05-0.5
Elongation, %	10-100	2-10
Fr. toughness, MPam ^{1/2}	0.002-0.1	0.01-0.1
Vickers hardness, H _v	-	0.1-1.2
Yld. strength, MPa	0.02-0.07	0.4-12
Service temp., C	70-110	80-150
Specific heat, J/kg·K	1750-2260	1120-1910
Th. conduct., W/m·K	0.04-0.08	0.03-0.6
Th. expansion, 10 ⁻⁶ /K	115-220	20-70

Eco-Attributes

Energy content, MJ/kg	150-190	150-180
Carbon footprint, CO ₂ (kg/kg)	N/A	N/A
Recycle potential	low	low

Aesthetic Attributes

Low (o), High Pitch (10)	1-2	3-4
Muffled (o), Ringing (10)	1-2	3-4
Soft (o), Hard (10)	1-2	3-4
Warm (o), Cool (10)	8-9	8-9

Features (Relative to Other Polymers)

Soft	Stiff and light
Resilient	Buoyant
Energy absorbant	Energy absorbant

Polymer Composites

Polymers/Glass Fiber (GFRP), Fiberglass

GFRP, the first of the modern fiber composites, was developed after WWI as a lightweight material with high strength and stiffness. It is made of continuous or chopped glass fibers in a polymer matrix – usually polyester or epoxy. Epoxy is more expensive than polyester, but gives better properties. Glass fibers are much cheaper than carbon or Kevlar, and therefore are widely used despite having lower stiffness than carbon and lower strength than Kevlar (glass accounts for 98% of the fiber market).

Design Notes The stiffness of GFRP is limited by the relatively low modulus of the glass fibers. The matrix material limits the operating environment to less than 120°C. Moisture can degrade properties. Short, discontinuous fibers can give a tensile strength of almost 50% that of the corresponding continuous fiber at a considerably reduced processing cost. GFRPs can be filled and colored to order. To reduce the possibility of delamination, cracking and splitting, holes, abrupt section changes, and sharp corners should be avoided. There are several grades of glass fiber, differing in composition and properties. e-glass is the standard reinforcement. c-glass has better corrosion resistance than e; r and s have better mechanical properties than e but are more expensive. ar-glass resists alkalis, allowing it to be used to reinforce cement. Thermosetting resins such as polyesters and epoxies are usually supplied as viscous syrups that wet and penetrate the fibers, setting when mixed with a catalyst. Thermoplastic resin such as polypropylene or polyamide are solids that soften on heating; the difficulty is to get them to mix well with the glass.

Typical Uses Boat hulls, train seats, pressure vessels, automobile components, sports equipment, bathroom, and kitchen fixtures.

Polymers/Carbon Fiber (CFRP)

CFRPs are the materials of sport and aerospace. They are made of carbon fibers embedded in a polymer matrix, usually epoxy or polyester. Carbon fibers have very high strength and stiffness, and they are light – much lighter than glass. This makes CFRPs the composite choice for aerospace, structural, and other applications that require high performance. Epoxy is more expensive than the competing polyester, but gives better properties and better adhesion to the fibers, giving the composite excellent fatigue resistance. CFRP is increasingly used to replace aluminum in aircraft structures in order to reduce weight – the US Air Force has been flying aircraft with structural CFRP components since 1972.

Design Notes Carbon has a higher modulus than glass and is much more expensive, limiting CFRP, to applications in which high stiffness is important. It is usually black because of the color of the fibers, but the matrix can be tinted. To reduce the possibility of delamination, cracking and splitting, holes, abrupt section changes, and sharp corners should be avoided. CFRPs have good creep and fatigue resistance, low thermal expansion, low friction and wear, vibration-damping characteristics, and environmental stability. They can be electrically conducting, making them opaque to radio waves. They are used mainly as continuous fiber reinforcement for epoxy resins, and, more recently, in thermoplastic resins such as PP or PEEK. The fibers come in four grades: high modulus (HM), high strength (HS), ultra high modulus (UHM), and ultra high strength (UHS) – with cost increasing in that order. Thermosetting resins such as polyesters and epoxies are usually supplied as viscous syrups that wet and penetrate the fibers, setting when mixed with a catalyst. As with CFRP, the matrix limits the maximum use temperature of the composite to 120°C, and it can absorb water – they are not good in hot, wet environments.

Typical Uses Aircraft structures, power boats, racing cars, tennis rackets, fishing rods, golf club shafts, performance bicycles.

Polymer Composites, continued**Attributes of (Quasi-Isotropic) Polymer Composites**

	GFRP	CFRP	KFRP
Price, \$/kg	9-20	50-61	120-140
Density, Mg/m ³	1.75-1.95	1.55-1.6	1.37-1.40

Technical Attributes

El. modulus, GPa	21-35	50-60	23-30
Elongation, %	0.8-1	0.3-0.35	0.3-0.4
Fr. toughness, MPam ^{1/2}	6-25	6-15	6-40
Vickers hardness, H _v	12-22	12-23	10-21
Yld. strength, MPa	200-500	500-1050	130-150
Service temp., °C	140-220	140-220	120-200
Specific heat, J/kg·K	1000-1200	900-1000	510-680
Th. conduct., W/m·K	0.4-0.5	1.3-2.6	0.20-0.26
Th. expansion, 10 ⁻⁶ /K	8.6-11	2-4	9.4-15

Eco-Attributes

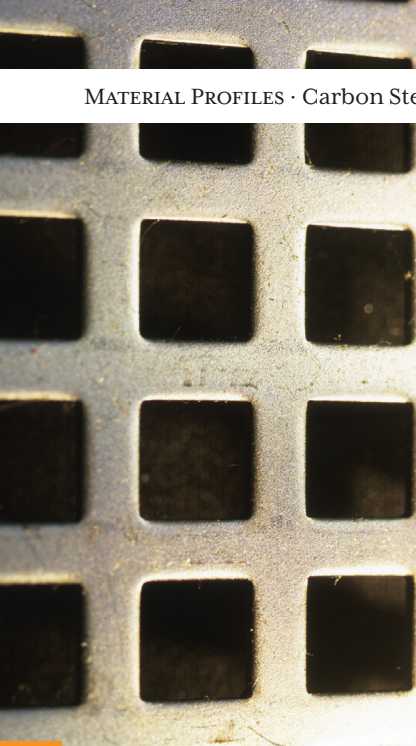
Energy content, MJ/kg	250-300	600-800	400-500
Carbon footprint, CO ₂ (kg/kg)	10	35	11
Recycle potential	Low	Low	Low

Aesthetic Attributes

Low (o), High Pitch (10)	5-6	7-8	5-6
Muffled (o), Ringing (10)	4-5	5-6	4-5
Soft (o), Hard (10)	6-7	7-8	6-7
Warm (o), Cool (10)	5-6	5-6	5-6

Features (Relative to Other Polymers)

Low cost	Stiff and light	Exceptionally lightweight
Corrosion resistant	Strong and light	Stiff and strong
Impact resistant	Durable	Tough



Attributes of Carbon Steels

Price, \$/kg	0.40–0.60
Density, Mg/m ³	7.8–7.9

Technical Attributes

El. modulus, GPa	200–216
Elongation, %	4–47
Fr. toughness, MPa·m ^{1/2}	12–92
Vickers hardness, H _v	120–650
Yld. strength, MPa	250–1755
Service temp., °C	–70–360
Specific heat, J/kg·K	440–520
Th. conduct., W/m·K	45–55
Th. expansion, 10 ^{–6} /K	10–14

Eco-Attributes

Energy content, MJ/kg	57–72
Carbon footprint, CO ₂ (kg/kg)	1.8
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	9
Muffled (o), Ringing (10)	6–7
Soft (o), Hard (10)	9
Warm (o), Cool (10)	9
Reflectivity, %	59

Features (Relative to Other Metals)

Stiff and strong
Tough
Cheap

Carbon Steels

What Are They? Think of steel and you think of railroads, oilrigs, tankers, and skyscrapers. And what you are thinking of is not just steel, it is carbon steel. That is the metal that made them possible – nothing else is at the same time so strong, so tough, so easily formed – and so cheap.

Design Notes Carbon steels are alloys of iron with carbon. Low carbon or “mild” steels have the least carbon – less than 0.25%. They are relatively soft, easily rolled to plate, I-sections or rod (for reinforcing concrete), and are the cheapest of all structural metals – it is these that are used on a huge scale for reinforcement, for steel-framed buildings, ship plate, and the like. Medium carbon steel (0.25–0.5% carbon) hardens when quenched – a quality that gives great control over properties. “Hardenability” measures the degree to which it can be hardened in thick sections; plain carbon steels have poor hardenability – additional alloying elements are used to increase it (see Low Alloy Steels). Medium carbon steels are used on an enormous scale for railroad tracks; there are many other lower-volume applications. High carbon steels (0.5–1.6% carbon) achieve even greater hardness, sufficient for them to be used as cutting tools, chisels, and cables, and “piano wire” – the metal strings of pianos and violins. More carbon than that and you have cast iron (1.6–4% carbon), easy to cast, but with properties that are less good than steel.

Typical Uses Low carbon steels are used so widely that no list would be complete. Reinforcement of concrete, steel sections for construction, sheet for roofing, car body panels, cans, and pressed sheet products give an idea of the scope. Medium carbon steels are the materials of general construction and engineering, axles and gears, bearings, cranks and shafts. High carbon steels are used for cutting tools, high performance bearings, cranks and shafts, springs, knives, ice axes, and ice skates.

Competing Materials In many applications carbon steels have no credible competition. Where higher hardenability and performance are sought, low alloy steels displace carbon steels. Where extreme corrosion resistance is necessary, stainless steels take over – but they are expensive.

The Environment The production energy of steel is comparatively low – per unit weight, about a half that of polymers; per unit volume, though, twice as much. Carbon steels are easy to recycle, and the energy to do so is small.

Technical Notes The two standard classifications for steels, the AISI and the SAE standards, have now been merged. In the SAE-AISI system, each steel has a four-digit code. The first two digits indicate the major alloying elements. The second two give the amount of carbon, in hundredths of a percent. Thus the plain carbon steels have designations starting 10xx, 11xx, 12xx, or 14xxx, depending on how much manganese, sulfur, and phosphorus they contain. The common low-carbon steels have the designations 1015, 1020, 1022, 1117, 1118; the common medium carbon steels are 1030, 1040, 1050, 1060, 1137, 1141, 1144, and 1340; the common high carbon steels are 1080 and 1095.

Stainless Steels

What Are They? Stainless steels are alloys of iron with chromium, nickel, and – often – four of five other elements. The alloying transmutes plain carbon steel that rusts and is prone to brittleness below room temperature into a material that does neither. Indeed, most stainless steels resist corrosion in most normal environments, and they remain ductile to the lowest of temperatures.

Design Notes Stainless steel must be used efficiently to justify its higher costs, exploiting its high strength, and corrosion resistance. Economic design uses thin, rolled gauge, simple sections, concealed welds to eliminate refinishing, and grades that are suitable to manufacturing (such as free machining grades when machining is necessary). Surface finish can be controlled by rolling, polishing, or blasting. Stainless steels are selected, first, for their corrosion resistance, second, for their strength and third, for their ease of fabrication. Most stainless steels are difficult to bend, draw, and cut, requiring slow cutting speeds and special tool geometry. They are available in sheet, strip, plate, bar, wire, tubing, and pipe, and can be readily soldered and braised. Welding stainless steel is possible but the filler metal must be selected to ensure an equivalent composition to maintain corrosion resistance. The 300 series are the most weldable; the 400 series are less weldable.

Typical Uses Railway cars, trucks, trailers, food-processing equipment, sinks, stoves, cooking utensils, cutlery, flatware, architectural metalwork, laundry equipment, chemical-processing equipment, jet-engine parts, surgical tools, furnace and boiler components, oil-burner parts, petroleum-processing equipment, dairy equipment, heat-treating equipment, automotive trim.

Competing Materials Carbon steel, plated, or painted; nickel based alloys; titanium and its alloys.

The Environment Stainless steels are FDA approved – indeed, they are so inert that they can be implanted in the body. All can be recycled.

Technical Notes Stainless steels are classified into four categories: the 200 and 300 series austenitic (Fe-Cr-Ni-Mn) alloys, the 400 series ferritic (Fe-Cr) alloys, the martensitic (Fe-Cr-C) alloys also form part of the 400 series, and precipitation hardening or PH (Fe-Cr-Ni-Cu-Nb) alloys with designations starting with S. Austenitic stainless steels have excellent resistance to pitting and corrosion, and are non-magnetic (a way of identifying them). Typical is the grade 304 stainless steel: 74% iron, 18% chromium, and 8% nickel. Here the chromium protects by creating a protective Cr_2O_3 film on all exposed surfaces. Nickel stabilizes face-centered cubic austenite, giving ductility, and strength both at high and low temperatures.



Attributes of Stainless Steels

Price, \$/kg	1.20–8.50
Density, Mg/m ³	7.4–8.1

Technical Attributes

El. modulus, GPa	189–210
Elongation, %	0.5–70
Fr. toughness, MPa·m ^{1/2}	12–280
Vickers hardness, H _v	130–600
Yld. strength, MPa	170–2090
Service temp., °C	–270–850
Specific heat, J/kg·K	400–530
Th. conduct., W/m·K	11–29
Th. expansion, 10 ^{–6} /K	9–20

Eco-Attributes

Energy content, MJ/kg	83–115
Carbon footprint, CO ₂ (kg/kg)	5.0
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	8–9
Muffled (o), Ringing (10)	6–7
Soft (o), Hard (10)	9
Warm (o), Cool (10)	7–8
Reflectivity, %	60–80

Features (Relative to Other Metals)

Durability
Extremes of temperature
Stiff and strong

**Attributes of Low Alloy Steels**

Price, \$/kg	0.40–0.90
Density, Mg/m ³	7.8–7.9

Technical Attributes

El. modulus, GPa	201–217
Elongation, %	3–38
Fr. toughness, MPa·m ^{1/2}	14–210
Vickers hardness, H _v	140–700
Yld. strength, MPa	245–2255
Service temp., °C	–70–660
Specific heat, J/kg·K	410–530
Th. conduct., W/m·K	34–55
Th. expansion, 10 ^{–6} /K	10.5–13.5

Eco-Attributes

Energy content, MJ/kg	60–83
Carbon footprint, CO ₂ (kg/kg)	2.0
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	9–9
Muffled (o), Ringing (1o)	6–8
Soft (o), Hard (1o)	9
Warm (o), Cool (1o)	8–9
Reflectivity, %	40–60

Features (Relative to Other Metals)

Exceptionally strong
Stiff and strong
Relatively cheap

Low Alloy Steels

What Is It? Pure Iron is soft stuff. Add carbon and heat-treat it right, and you can get an a material that is almost as hard and brittle as glass or as ductile and tough as boiler plate. “Heat treat” means heating the steel to about 800 °C to dissolve the carbon, then quenching (rapid cooling, often by dropping into cold water), and tempering – reheating it to a lower temperature and holding it there. Quenching turns the steel into hard, brittle “martensite”; tempering slowly restores the toughness and brings the hardness down. Control of tempering time and temperature gives control of properties. It’s wonderful what 1% of carbon can do. But (the inevitable “but”) the cooling rate in that initial quench has to be fast – more than 200 °C/second for plain carbon steels. There is no difficulty in transforming the surface of a component to martensite, but the interior cools more slowly because heat has to be conducted out. If the component is more than a few millimeters thick, there is a problem – the inside doesn’t cool fast enough. The problem is overcome by alloying. Add a little manganese, Mn, nickel, Ni, molybdenum, Mo or chromium, Cr, and the critical cooling rate comes down, allowing thick sections to be hardened and then tempered. Steels alloyed for this purpose are called “low alloy steels,” and the property they have is called “hardenability.”

Design Notes Low alloy steels are heat treatable – most other carbon steels are not – and so are used for applications where hardness or strength is an important feature, particularly in large sections. They have greater abrasion resistance, higher toughness, and better strength at high temperatures than plain carbon steels. Alloy steels with carbon content of 0.30–0.37% are used for moderate strength and great toughness; 0.40–0.42% for higher strength and good toughness; 0.45–0.50% for high hardness and strength with moderate toughness; 0.50–0.62% for hardness (springs and tools); 1% for high hardness and abrasion resistance (ball bearings or rollers).

Typical Uses Springs, tools, ball bearings, rollers; crankshafts, gears, connecting rods.

Competing Materials Carbon steels, stainless steels.

The Environment Steels are not particularly energy-intensive to make, and are easily and widely recycled.

Technical Notes The SAE-AISI system for low alloy steels works the same way as that for plain carbon steels. Each steel has a four-digit code; the first two digits indicate the major alloying elements, the second two give the amount of carbon, in hundredths of a percent. Typical are the nickel-chrome-molybdenum steels with the designation 43xx, but the alloying elements can include any of the following: more than 2% silicon, more than 0.4% copper, more than 0.1% molybdenum, more than 0.5% nickel, more than 0.5% chromium.

Aluminum Alloys

What Are They? Aluminum was once so rare and precious that the Emperor Napoleon III of France had a set of cutlery made from it that cost him more than silver. But that was 1860; today, 150 years later, aluminum spoons are things you throw away – a testament to our ability to be both technically creative and wasteful. Aluminum, the first of the “light alloys” (with magnesium and titanium), is the third most abundant metal in the earth’s crust (after iron and silicon) but extracting it costs much energy. It has grown to be the second most important metal in the economy (steel comes first), and the mainstay of the aerospace industry.

Design Notes Aluminum alloys are light, can be strong and are easily worked. Pure aluminum has outstanding electrical and thermal conductivity (copper is the only competition here) and is relatively cheap – though still more than twice the price of steel. It is a reactive metal – in powder form it can explode – but in bulk an oxide film (Al_2O_3) forms on its surface, protecting it from corrosion in water and acids (but not strong alkalis). Aluminum alloys are not good for sliding surfaces – they scuff – and the fatigue strength of the high strength alloys is poor. Nearly pure aluminum (1000 series alloys) is used for small appliances and siding; high strength alloys are used in aerospace (2000 and 7000 series); and extrudable, medium strength alloys are used in the automotive and general engineering sectors (6000 series).

Typical Uses Aerospace engineering; automotive engineering; die-cast chassis for household and electronic products; siding for buildings; foil for containers and packaging; beverage cans; electrical and thermal conductors.

Competing Materials Magnesium, titanium, CFRP for lightweight structures; steel for cans; copper for conductors.

The Environment Aluminum ore is abundant. It takes a lot of energy to extract aluminum, but it is easily recycled at low energy cost.

Technical Notes Until 1970, designations of wrought aluminum alloys were a mess; in many countries, they were simply numbered in the order of their development. The International Alloy Designation System (IADS), now widely accepted, gives each wrought alloy a four-digit number. The first digit indicates the major alloying element or elements. Thus the series 1xxx describe unalloyed aluminum; the 2xxx series contain copper as the major alloying element, and so forth. To these serial numbers are added a suffix F, O, H, or T indicating the state of hardening or heat treatment. In the AAUS designation for cast alloys, the first digit indicates the alloy group. In the 1xx.x group, the second two digits indicate the purity; in the other groups it indicates the alloying elements. In the 2xx.x to 9xx.x groups, the second two digits are simply serial numbers. The digit to the right of the decimal point indicates the product form: 0 means “castings” and 1 means “ingot.”



Attributes of Aluminum Alloys

Price, \$/kg	1.30–5.70
Density, Mg/m ³	2.50–2.95

Technical Attributes

El. modulus, GPa	68–88.5
Elongation, %	1–44
Fr. toughness, MPa·m ^{1/2}	18–40
Vickers hardness, H _v	20–150
Yld. strength, MPa	30–510
Service temp., °C	–270–180
Specific heat, J/kg·K	857–990
Th. conduct., W/m·K	76–235
Th. expansion, 10 ^{–6} /K	16–24

Eco-Attributes

Energy content, MJ/kg	235–335
Carbon footprint, CO ₂ (kg/kg)	13
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	8–9
Muffled (o), Ringing (10)	5–8
Soft (o), Hard (10)	8–9
Warm (o), Cool (10)	9–10
Reflectivity, %	80–92

Features (Relative to Other Metals)

Lightweight
Corrosion resistant
Easy to recycle



Attributes of Magnesium Alloys

Price, \$/kg	2.60–11.40
Density, Mg/m ³	1.73–1.95

Technical Attributes

El. modulus, GPa	40–47
Elongation, %	1.5–20
Fr. toughness, MPa·m ^{1/2}	12–70
Vickers hardness, H _v	35–135
Yld. strength, MPa	65–435
Service temp., °C	–40–300
Specific heat, J/kg·K	950–1060
Th. conduct., W/m·K	50–156
Th. expansion, 10 ^{–6} /K	24.6–30

Eco-Attributes

Energy content, MJ/kg	300–500
Carbon footprint, CO ₂ (kg/kg)	35
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	8–9
Muffled (o), Ringing (10)	3–6
Soft (o), Hard (10)	8
Warm (o), Cool (10)	8–9
Reflectivity, %	68

Features (Relative to Other Metals)

- Exceptionally lightweight
- Easy to die-cast
- Adequate strength

Magnesium Alloys

What Are They? Magnesium is the second of the light metal trio (with partners aluminum and titanium) and light it is: a computer case made from magnesium is barely two-thirds as heavy as one made from aluminum. It and its partners are the mainstays of aerospace engineering.

Design Notes The push for compact, light, electronics (laptops, mobile phones), and lightweight vehicles (wheels, in-cabin metal parts) has prompted designers to look harder at magnesium alloys than ever before, and has stimulated production and driven prices down. What do they offer? Magnesium has a low density, good mechanical damping, much better thermal conductivity than steel, less good electrical conductivity than copper and aluminum but still good. It survives well in the protected environment of a house or office, but it corrodes badly in salt water and acids; even sweat is enough to tarnish it. Magnesium is flammable, but this is a problem only when its in the form of powder or very thin sheet. It costs more than aluminum but nothing like as much as titanium. It is easy to machine, but because of its low stiffness, parts must be firmly clamped while doing so. Magnesium alloys are designed for specific forming purposes. Some (like AZ31B) are good for extrusions. Others (AZ63, AZ92, and AM100) have been formulated for investment casting; the AZ91 range are used for die-casting. Most magnesium alloys can be welded using TIG or MIG methods; and soldering and adhesive bonding are both feasible. Spot and seam welds are possible but only in low stress applications; riveting is better, provided aluminum rivets are used to avoid galvanic corrosion.

Typical Uses Aerospace; automotive; sports goods; nuclear fuel cans; vibration damping and shielding of machine tools; engine case castings; automotive wheels; ladders; housings for electronic equipment, office equipment, and lawnmowers.

Competing Materials Titanium, aluminum, CFRP.

The Environment Magnesium is the fifth most abundant metal in the earth's crust, and the third in its oceans – and it can be extracted economically from both (the Dead Sea, thick with dissolved salts – is the best source of all). But its extraction is very energy-intensive, consuming three times more per unit weight than commodity polymers and nearly twice as much as aluminum. It can be recycled, and doing this uses barely one-fifth as much energy.

Technical Notes The classification system of the American Society for Testing Materials (ASTM) is the most widely used. In this system, the first two letters indicate the principal alloying elements. The letter corresponding to the element present in the greatest quantity is used first; if they are equal, they are listed alphabetically. The letters are followed by numbers which represent the nominal compositions of the principal alloying elements in weight percent rounded to the nearest whole number; thus AZ91 means the alloy 90% Mg, 9% Al and 1% Zn.

Titanium Alloys

What Are They? Titanium is the seventh most abundant metal in the earth's crust, but extracting the metal from the oxide in which it occurs naturally is unusually difficult. This makes titanium, third member of the light alloy trio, by far the most expensive of the three (more than ten times the price of aluminum). Despite this, the use of titanium is growing, propelled by its remarkable properties. It has a high melting point (1660°C), it is light, and – although reactive – it resists corrosion in most chemicals, protected by a thin film of oxide on its surface. Titanium alloys are exceptionally strong for their weight, and can be used at temperatures up to 500°C – compression blades of aircraft turbines are made of them. They have unusually poor thermal and electrical conductivity and low expansion coefficients.

Design Notes Titanium alloys are expensive, requiring vacuum processing to prevent take up of oxygen, which makes them brittle. But they are unusually strong, light, and corrosion resistant, so much so that pure titanium can be implanted in the body to repair broken bones. More usually it is alloyed with aluminum and vanadium (Ti with 8% Al 6%V, or simply Ti-6-4) to give a material that can be forged and worked yet has good resistance to creep. Titanium alloys have limited ductility – sheet cannot easily be bent to radii less than 1.5 times its thickness. They can – with difficulty – be welded, but are easy to diffusion bond. The drive to miniaturize consumer electronics gives titanium a growing importance in product design. The casings of mobile phones and portable computers are now so thin that polymers cannot take the strain – they are not stiff or strong enough. The strength and low density of titanium makes it – despite its cost – an attractive replacement.

Typical Uses Aircraft turbine blades; general aerospace applications; chemical engineering; heat exchangers; bioengineering; medical; missile fuel tanks; heat exchangers, compressors, valve bodies, surgical implants, marine hardware, paperpulp equipment, casings for mobile phones, and portable computers.

Competing Materials Magnesium, aluminum, CFRP.

The Environment Extracting titanium from its ores is very energy-intensive. It can be recycled provided it is not contaminated with oxygen.

Technical Notes There are four groups of titanium alloys: α alloys, near- α alloys, α - β alloys, and β alloys. The α alloys are hcp, the β alloys are bcc. α alloys are preferred for high temperature applications because of their creep resistance and for cryogenic applications because of their good toughness at low temperatures. A designation system with some logic to it simply lists the quantities of the principal alloying additions; thus “Ti-8-1-1” contains 8% aluminum, 1% molybdenum, and 1% vanadium; and “Ti-6-4” means 6% aluminum and 4% vanadium.



Attributes of Titanium Alloys

Price, \$/kg	21.00–28.00
Density, Mg/m ³	4.36–4.84

Technical Attributes

El. modulus, GPa	90–137
Elongation, %	1–40
Fr. toughness, MPa·m ^{1/2}	14–120
Vickers hardness, H _v	60–380
Yld. strength, MPa	172–1245
Service temp., °C	–40–500
Specific heat, J/kg·K	510–650
Th. conduct., W/m·K	3.8–20.7
Th. expansion, 10 ^{–6} /K	7.9–11

Eco-Attributes

Energy content, MJ/kg	750–1250
Carbon footprint, CO ₂ (kg/kg)	46
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	8–9
Muffled (o), Ringing (10)	5–8
Soft (o), Hard (10)	8–9
Warm (o), Cool (10)	7–8
Reflectivity, %	44–53

Features (Relative to Other Metals)

Exceptionally strong
Exceptionally corrosion
resistant
Tough



Attributes of Nickel Alloys

Price, \$/kg	4.30–28.60
Density, Mg/m ³	7.65–9.3

Technical Attributes

El. modulus, GPa	125–245
Elongation, %	0.3–70
Fr. toughness, MPa·m ^{1/2}	65–150
Vickers hardness, H _v	75–600
Yld. strength, MPa	70–2100
Service temp., °C	–200–1200
Specific heat, J/kg·K	365–565
Th. conduct., W/m·K	8–91
Th. expansion, 10 ^{–6} /K	0.5–16.5

Eco-Attributes

Energy content, MJ/kg	40–690
Carbon footprint, CO ₂ (kg/kg)	12
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	8–9
Muffled (o), Ringing (10)	3–6
Soft (o), Hard (10)	8
Warm (o), Cool (10)	8–9
Reflectivity, %	50–65

Features (Relative to Other Metals)

Exceptionally corrosion resistant
High temperatures
Stiff, strong, and tough

Nickel Alloys

What Is It? The US 5¢ piece, as its name suggests, is made of pure nickel. Look at one – much can be learned from it: that nickel is a ductile, silvery metal, easily formed by stamping (or rolling or forging), hard when worked, and with good resistance to corrosion. Not bad for 5¢. What it does not reveal is that nickel has two more remarkable sets of properties. One is the effect it has when alloyed with steel, stabilizing the face-centered cubic structure that gives the ductility and corrosion resistance to stainless steel (its largest single use). The other is its strength at high temperatures, a strength that can be boosted by alloying to make the materials on which all aircraft jet engines depend. These alloys have properties so extreme that they are known as “super alloys.”

Design Notes Pure nickel has good electrical conductivity, thermal conductivity and strength and corrosion resistance; nickel and its alloys are used in marine applications for heat exchanges in other structures. Nickel-iron alloys have high magnetic permeability (good for electronic shielding and magnetic coils) and low thermal expansion (good for glass-to-metal joints). Invar, an alloy based on nickel, has essentially a zero thermal expansion coefficient near room temperature; a magnetic contraction counteracts the ordinary thermal expansion, canceling it out. Nickel-chrome-iron alloys have high electrical resistance and are used as heating elements in toasters and industrial furnaces. Bi-metallic sheet of nickel bonded to copper is used as actuators for thermostats and safety devices. Nickel alloys based on the combination nickel-titanium-aluminum have exceptionally high temperature strength, toughness, and resistance to attack by gasses. These super alloys, carrying trade names such as Nimonic, Inconel, and Hastelloy are used for turbine blades, disks and combustion chambers, chemical engineering equipment, and high temperature design.

Typical Uses The principal uses of nickel are an alloying element in stainless steels and super alloys; blades, disks, and combustion chambers in turbines and jet engines, rocket engines, bi-metallic strips, thermocouples, springs, food equipment, heating wires, electroplating for corrosion protection, coinage, and nickel-cadmium batteries.

Competing Materials Iron based super alloys (lower in performance); cobalt-based super alloys (more expensive); stainless steels.

The Environment About 10% of the population is sensitive to nickel, causing them to react even to the nickel in stainless steel watch straps. Compounds of nickel can be more toxic; nickel carbonyl, used in the extraction of nickel, is deadly.

Technical Notes 8% of nickel, added to steel, stabilizes austenite, making the steel ductile down to cryogenic temperatures. Nickel in super alloys combines with other alloying elements, particularly titanium and aluminum, to form precipitates of intermetallic Ni₃Al and Ni₃Ti.

Zinc Alloys

What Are They? The slang in French for a bar or pub is “le zinc,” bar counters in France used to be clad in zinc – many still are – to protect them from the ravages of wine and beer. Bar surfaces have complex shapes – a flat top, curved profiles, rounded, or profiled edges. These two sentences say much about zinc: it is hygienic; it survives exposure to acids (wine), to alkalis (cleaning fluids), to misuse (drunk customers), and it is easy to shape. These remain among the reasons it is still used today. Another is the “castability” of zinc alloys – their low melting point and fluidity give them a leading place in die-casting. The molds are relatively cheap, and details are accurately reproduced.

Design Notes Most zinc is used in galvanizing steel to improve corrosion resistance. Zinc die-casting alloys are strong enough for most consumer products; and the metal itself is cheap. They are the metallic answer to injection molded polymers. Zinc alloys offer higher strength than other die-casting alloys except those of copper. Die-cast parts can be held to close tolerances in thin sections and are easily machined. Wrought zinc is available as strip, sheet, foil, plate, rod, wire, and blanks for forging or extrusion. Bends in rolled zinc sheet should be at right angles to the grain or rolling direction and should have a radius no less than the sheet thickness.

Typical Uses Roofing, gutters, flashlight reflectors, fruit jar caps, radio shielding, gaskets, photoengraving plates, handles, gears, automotive components, kitchen countertops, protective plating.

Competing Materials Product design: die-cast aluminum alloys, thermoplastics that can be injection molded; corrosion protection; nickel, chrome plating, polymer powder coating and stainless steel.

The Environment Zinc vapor is toxic – if you inhale it you get the “spelter-shakes” – but adequate protection is now universal. In all other ways zinc is a star: it is non-toxic, has low energy content and – in bulk – can be recycled (not, of course, as plating).

Technical Notes Most zinc alloys are die-cast; for this, the prime alloys are AC40A and AC41A. Wrought zinc is made by hot rolling cast sheets, by extrusion, or by drawing. Zinc foil is made by electroplating zinc on an aluminum drum and then stripping it off. Super-plastic zinc alloys can be formed by methods normally used for polymers – vacuum forming, compression molding – as well as traditional metal processes like deep drawing and impact extrusion. Extrusion and forging is done with zinc-manganese alloys. Wrought zinc alloys are easily soldered and spot welded. Zinc is frequently left uncoated. It can be polished, textured, plated, or painted.



Attributes of Zinc Alloys

Price, \$/kg	0.90–2.90
Density, Mg/m ³	5.5–7.2

Technical Attributes

El. modulus, GPa	60–110
Elongation, %	1–90
Fr. toughness, MPa·m ^{1/2}	10–130
Vickers hardness, H _v	30–160
Yld. strength, MPa	50–450
Service temp., °C	–45–120
Specific heat, J/kg·K	380–535
Th. conduct., W/m·K	95–135
Th. expansion, 10 ^{–6} /K	14–40

Eco-Attributes

Energy content, MJ/kg	50–145
Carbon footprint, CO ₂ (kg/kg)	4.1
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (10)	8
Muffled (o), Ringing (10)	4–7
Soft (o), Hard (10)	8–9
Warm (o), Cool (10)	9
Reflectivity, %	74–85

Features (Relative to Other Metals)

Easily die-cast
Corrosion resistant
Easily machined

Copper, Brass, Bronze

What Are They? In Victorian times you washed your clothes in a “copper” – a vat or tank of beaten copper sheet, heated over a fire; the device exploited both the high ductility and the thermal conductivity of the material. Copper has a distinguished place in the history of civilization: it enabled the technology of the Bronze age (3000–1000 BC). It is used in many forms: as pure copper, as copper-zinc alloys (brasses), as copper-tin alloys (bronzes), and as copper-nickel, and copper-beryllium. The designation of “copper” is used when the percentage of copper is more than 99.3%.

Design Notes Copper and its alloys are easy to cast, to roll, to sheet, to draw, to wire, and to shape in other ways. They resist corrosion in the atmosphere, acquiring an attractive green patina (copper carbonate) in clean air, and a black one (copper sulfide) in one that is not – copper roofs in cities are usually black. The patina of bronze is a rich warm brown, much loved by sculptors. Pure copper has excellent electrical and thermal conductivity, is easy to fabricate and join, has good corrosion resistance and reasonable strength. Where high conductivity is necessary, oxygen-free high conductivity (OFHC) copper is used. In its annealed form it is soft and ductile; with work hardening the material becomes harder but less ductile. In brasses and bronzes the alloying increases the strength. The commonest are the “cartridge brasses” (used in musical instruments, hardware and – of course – ammunition), “yellow brasses” (used in springs and screws) and “Muntz metals” (used in architectural applications and condenser tubes). Cartridge brass, with 30% zinc, has the highest ductility and is used to draw brass wires. Bronzes are exceptionally liquid when molten, allowing them to be cast to intricate shapes.

Typical Uses Electrical conductors, heat exchangers, coinage, pans, kettles and boilers, plates for etching and engraving, roofing and architecture, cast sculptures, printing wires, heat pipes, filaments, and musical instruments.

Competing Materials Aluminum for conductors and thermal conduction, stainless steel for cooking and protection.

The Environment Copper and its alloys are particularly easy to recycle – in many countries the recycle fraction approaches 90%.

Technical Notes There is now a UNS designation system for copper and its alloys: the letter C (for “copper”) followed by a five-digit number. Only the first digit means anything: C1**** designates almost pure copper, the C2, C3, and C4 series are brasses with increasing zinc content, the C5s are bronzes based on copper and tin, the C6s are other bronzes containing aluminum instead of tin, and the C7s are copper-nickel alloys.

Copper, Brass, Bronze, continued**Attributes of Copper, Brass, Bronze**

	Copper	Brass	Bronze
Price, \$/kg	1.72-1.93	1.43-2.00	3.72-5.44
Density, Mg/m ³	8.93-8.94	7.8-8.8	8.5-9

Technical Attributes

El. modulus, GPa	121-133	90-120	70-120
Elongation, %	4-50	5-55	2-60
Fr. toughness, MPa·m ^{1/2}	40-100	30-86	24-90
Vickers hardness, H _v	44-180	50-300	60-240
Yld. strength, MPa	45-330	70-500	65-700
Service temp., °C	-270-180	-270-220	-270-200
Specific heat, J/kg·K	372-388	372-383	382-385
Th. conduct., W/m·K	147-370	110-220	50-90
Th. expansion, 10 ⁻⁶ /K	16.8-17.9	16.5-20.7	16.5-19

Eco-Attributes

Energy content, MJ/kg	100-130	100-120	110-120
Carbon footprint, CO ₂ (kg/kg) 3.6	3.7	3.6	4.2
Recycle potential	High	High	High

Aesthetic Attributes

Low (o), High Pitch (10)	8-8	8-8	8-8
Muffled (o), Ringing (10)	6-9	6-9	5-10
Soft (o), Hard (10)	8-9	8-9	8-9
Warm to cool, 0-10	9-10	9-10	9-9
Reflectivity	51-91	50-90	50-80
Opaque			

Features (Relative to Other Metals)

Ductile and tough	Easily cast and machined	Corrosion resistant and durable
Easily shaped and joined	Excellent wear resistance	Resonant (chimes and bells)
Exceptional heat conductivity	Relatively cheap	Easily cast



Others

Attributes of Alumina (97.5%)

Price, \$/kg	4-12
Density, Mg/m ³	3.7-3.8

Technical Attributes

El. modulus, GPa	333-350
Elongation, %	0
Fr. toughness, MPa·m ^{1/2}	3.6-3.8
Vickers hardness, H _v	1400-1600
Tensile strength	175-200
Service temp., C	-270-1700
Specific heat, J/kg·K	635-700
Th. conduct., W/m·K	25-30
Th. expansion, 10 ⁻⁶ /K	6.7-7

Eco-Attributes

Energy content, MJ/kg	150-200
Carbon footprint, CO ₂ (kg/kg)	2.8
Recycle potential	Low

Aesthetic Attributes

Low (o), High Pitch (10)	8-9
Muffled (o), Ringing (10)	8-9
Soft (o), Hard (10)	8-9
Warm (o), Cool (10)	7-8

Features (Relative to Other Ceramics)

- Exceptionally high temperatures
- Exceptionally corrosion resistant
- Excellent electrical insulator

Technical Ceramics

Alumina

Alumina (Al₂O₃) is to technical ceramics what mild steel is to metals – cheap, easy to process, the work horse of the industry. It is the material of spark plugs and electrical insulators. In single crystal form it is sapphire, used for watch faces and cockpit windows of high speed aircraft. More usually it is made by pressing and sintering powder, giving grades ranging from 80 to 99.9% alumina; the rest is porosity, glassy impurities, or deliberately added components. Pure aluminas are white; impurities make them pink or green. The maximum operating temperature increases with increasing alumina content. Alumina has a low cost and a useful and broad set of properties: electrical insulation, high mechanical strength, good abrasion, and temperature resistance up to 1650 C, excellent chemical stability and moderately high thermal conductivity, but it has limited thermal shock and impact resistance. Chromium oxide is added to improve abrasion resistance; sodium silicate, to improve processability but with some loss of electrical resistance. Competing materials are magnesia, silica and borosilicate glass.

Typical Uses Insulators, heating elements, micro-electronic substrates, radomes, bone replacement, tooth replacement, tank armour, spark plug insulators, dies for wire drawing, nozzles for welding and sandblasting.

Boron Carbide

Boron carbide (B₄C) is nearly as hard as diamond and vastly less expensive (though still not cheap). Its very low density and high hardness make it attractive for the outer layer of bulletproof body armor and as an abrasive.

Typical Uses Lightweight armor, bulletproof surfaces, abrasives, sandblasting nozzles, high temperature thermocouples.

Tungsten Carbide

Tungsten carbide (WC) is most commonly used in the form of a “cemented” carbide, or cermet: a metal carbide held by a small amount (5-20%) of metallic binder, usually cobalt. Its exceptional hardness and stability make it an attractive material when wear resistance is essential. Its properties are governed by the type of carbide, grain size and shape, and the proportion of carbide to metal. Cermets are expensive but, as cutting tools, they survive cutting speeds ten times those of the best tool steel. Shaping is usually done by pressing, sintering, and then grinding; the tool bit is brazed to a shank or blade made from a cheaper steel. Tungsten carbide can be vapor-coated with Ti-nitride to improve wear resistance even further.

Typical Uses Cutting tools, saw blades, dental drills, oil drilling bits, dies for wire drawing, knife edges.

Silicon Carbide

Silicon carbide (SiC, carborundum), made by fusing sand and coke at 2200 C, is the grit on high quality sandpaper. It is very hard and maintains its strength to high temperature, has good thermal shock resistance, excellent abrasion resistance, and chemical stability, but, like all ceramics, it is brittle. Silicon carbide is a blue-black material. High strength SiC fibers such as Nicalon, made by CVD processes, are used as reinforcement in ceramic or metal matrix composites.

Typical Uses Cutting tools, dies and molding materials, catalytic converters, engine components, mechanical seals, sliding bearings, wear protection sleeves, heat exchange tubes, furnace equipment, heating elements.

Glass

Soda-Lime Glass

Soda-lime is the glass of windows, bottles, and light bulbs, used in vast quantities, the commonest of them all. The name suggests its composition: 13–17% NaO (the “soda”), 5–10% CaO (the “lime”), and 70–75% SiO₂ (the “glass”). It has a low melting point, is easy to blow and mold, and it is cheap. It is optically clear unless impure, when it is typically green or brown. Windows, today have to be flat and that was not – until 1950 – easy to do; now the float-glass process, solidifying glass on a bed of liquid tin, makes “plate” glass cheaply and quickly.

Typical Uses Windows, bottles, containers, tubing.

Borosilicate Glass

When most of the lime in soda-lime glass is replaced by borax, B₂O₃, it becomes borosilicate glass (“Pyrex”). It has a higher melting point than soda-lime glass and is harder to work; but it has a lower expansion coefficient and a high resistance to thermal shock, so its used for glass wear and laboratory equipment.

Typical Uses Laboratory glassware, ovenware, headlights, electrical insulators, metal/glass seals, telescope mirrors, sights, gages, piping.

Silica Glass

Silica is a glass of great transparency. It is nearly pure SiO₂, it has an exceptionally high melting point and is difficult to work, but, more than any other glass, it resists temperature and thermal shock.

Typical Uses Envelopes for high-temperature lamps.

Glass Ceramic

Glass ceramics are glasses that, to a greater or lesser extent, have crystallized. They are shaped while in the glassy state, using ordinary molding methods and then cooled in such a way that the additives they contain nucleate small crystals. It’s sold for cooking as Pyroceram and is used for high performance, heat-resisting applications.

Typical Uses Cookware, stove surfaces, high performance, heat-resisting applications.



Attributes of Soda-lime Glass

Price, \$/kg	0.68–1
Density, mg/m ³	2.44–2.5

Technical Attributes

El. modulus, GPa	68–72
Elongation, %	0
Fr. toughness, MPa·m ^{1/2}	0.55–0.7
Vickers hardness, H _v	440–480
Tensile strength	31–35
Service temp., C	–270–250
Specific heat, J/kg·K	850–950
Th. conduct., w/m·K	0.7–1.3
Th. expansion, 10 ^{–6} /K	9–9.5

Eco-Attributes

Energy content, MJ/kg	20–25
Carbon footprint, CO ₂ (kg/kg)	0.8
Recycle potential	High

Aesthetic Attributes

Low (o), High Pitch (1o)	7–8
Muffled (o), Ringing (1o)	8–9
Soft (o), Hard (1o)	7–8
Warm (o), Cool (1o)	5–6

Features (Relative to Other Glasses)

Optically clear
Easy to mold
Low cost

Natural Materials

Bamboo

Bamboo is nature's gift to the construction industry. Think of it: a hollow tube, exceptionally strong and light, growing so fast that it can be harvested after a year, and – given a little longer – reaching a diameter of 0.3 meters and a height of 15 meters. This and its hard surface and ease of working makes it the most versatile of materials. Bamboo is used for building and scaffolding, for roofs and flooring, for pipes, buckets, baskets, walking sticks, fishing poles, window blinds, mats, arrows, and furniture. Tonkin bamboo is strong and flexible (fishing poles); Tali bamboo is used for structural applications (houses or furniture); Eeta bamboo is the fastest growing and is used as a source of cellulose for the production of cellulose or Rayon.

Balsa

Balsa is another of nature's miracles: exceptionally light, buoyant and insulating, yet strong and stiff along the grain. Balsa is used for life preservers, buoys, floats, paneling, vibration isolation, insulating partitions, inside trim of aircraft, and model airplanes. Its main use today is as cores for sandwich hulls of yachts and power boats; here "end-grain" balsa is used, meaning that the grain lies at right angles to the face of the hull or panel.

Cork

Cork is the subcutaneous bark of the cork-oak, *Quercus Suber*. Its cellular structure is up to 80% air by volume. When dried, cork is light, porous, easily compressed, and elastic. It has a low thermal conductivity, chars at 120 C, and ignites only with difficulty when in contact with flame. Cork is a natural closed-cell foam and is waterproof and remarkably stable, surviving in the neck of a wine bottle for up to 30 years without decay or contaminating the wine. Corkboard, made by compressing granulated cork under heat, is used for wall and ceiling insulation against heat and sound. Cork is used for bottle stoppers, insulation, vibration control, floats, insulation, and packaging for fruit transportation. In pressed form it is used for gaskets, oil retainers and polishing wheels, and as a component of linoleum.

Leather

Leather is a natural fabric. It has high tensile strength and is exceptionally tough and resilient, yet it is flexible and – as suede – is soft to touch. It is prepared by the tanning of animal hide, a smelly process in which the hide is soaked in solutions of tannins for weeks or months, making it pliable and resistant to decay. Leather is used for belts, gaskets, shoes, jackets, handbags, linings, and coverings.

Wood

Wood has been used to make products since the earliest recorded time. The ancient Egyptians used it for furniture, sculpture, and coffins before 2500 BC. The Greeks at the peak of their empire (700 BC) and the Romans at the peak of theirs (around 0 AD) made elaborate boats, chariots, and weapons of wood, and established the craft of furniture making that is still with us today. More diversity of use appeared in Medieval times, with the use of wood for large-scale building, and mechanisms such as pumps, windmills, even clocks, so that, right up to end of the 17th century, wood was the principal material of engineering. Since then cast iron, steel, and concrete have displaced it in some of its uses, but timber continues to be used on a massive scale.

Wood offers a remarkable combination of properties. It is light, and, parallel to the grain, it is stiff, strong and tough – as good, per unit weight, as any man-made material. It is cheap, it is renewable, and the fossil-fuel energy needed to cultivate and harvest it is outweighed by the energy it captures from the sun during growth. It is easily machined, carved and joined, and – when laminated – it can be molded to complex shapes. And it is aesthetically pleasing, warm both in color and feel, and with associations of craftsmanship and quality.



Metal Foams

What Are They? Metals that float in water? Doesn't sound sensible. Yet metal foams do – some have densities that are less than one-tenth of that of H_2O . They are a new class of material, as yet imperfectly characterized, but with alluring properties. They are light and stiff, they have good energy-absorbing characteristics (making them good for crash protection and packaging), and they have attractive heat-transfer properties (used to cool electronic equipment and as heat exchangers in engines). Some have open cells, very much like polymer foams but with the characteristics of metals (ductility, electrical conductivity, weldability, and so forth). Others have closed cells, like “metallic cork.” And they are visually appealing, suggesting use in industrial design. Metal foams are made by casting methods that entrap gas in the semi-liquid metal, or by a replication technique using a polymer foam as a precursor. Once cast, they are as chemically stable as the metal from which they were made, have the same melting point and specific heat, but greatly reduced density, stiffness, and strength. The stiffness-to-weight and strength-to-weight ratios, however, remain attractive.

At this point in time there are some 12 suppliers marketing a range of metal foams, mostly based on aluminum, but other metals – copper, nickel, stainless steel and titanium – can be foamed.

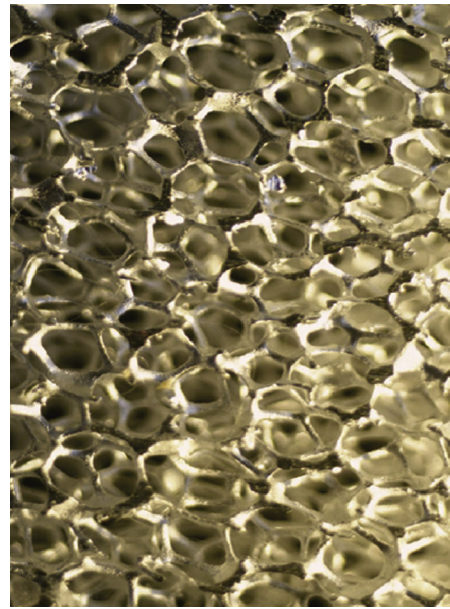
Design Notes There is little to go on here. Metal foams can be machined, and some can be cast to shape but this at present is a specialized process. They are best joined by using adhesives, which gives a strong bond. Some have a natural surface skin with an attractive texture, but this is lost if the foam is cut. The most striking characteristics of the materials are their low weight, good stiffness, and the ability to absorb energy when crushed.

Potential Uses Metal foams have promise as cores for light and stiff sandwich panels; as stiffeners to inhibit buckling in light shell structures; as energy-absorbing units, both inside and outside of motor vehicles and trains; and as efficient heat exchanges to cool high powered electronics (by blowing air through the open cells of the aluminum foam, attached to the heat source). Industrial designers have seen potential in exploiting the reflectivity and light filtering of open-cell foams, and the interesting textures of those with closed cells.

Competing Materials Rigid polymer foams; aluminum honeycombs; woods.

The Environment Metal foams are not flammable (unlike most other foams) and they can be recycled.

Suppliers Shinko Wire Company Ltd., 10-1 Nakahama-machi, Amagasaki-shi 660, Japan. Phone 81-6-411-1081; Fax 81-6-411-1056; ERG Materials and Aerospace Corp., 900 Stanford Ave., Oakland, CA 94608, USA. Phone 1-510-658-9785; Fax 1-510-658-7428; Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM), Wiener Strasse 12, D-29359, Bremen, Germany. Phone 49-421-2246-211; Fax 49-421-2246-300.



Attributes of Closed-cell Aluminum Foam

Price, \$/kg	12.00–20.00
Density, Mg/m ³	0.07–0.5

Technical Attributes

El. modulus, GPa	0.02–2
Fr. toughness, MPa·m ^{1/2}	0.03–0.5
Vickers hardness, H _v	0.08–1
Yield strength, MPA	0.025–30
Service temp., C	–100–200
Th. conduct., W/m·K	0.3–10
Th. expansion, 10 ^{–6} /K	19–21

Eco-Attributes

Energy content, MJ/kg	250–290
Carbon footprint, CO ₂ (kg/kg)	22
Recycle potential	High

Aesthetic Attributes

Reflectivity, %	5–10
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Features (Relative to Other Metals)

Lightweight
Stiff
High temperatures



Amorphous Metals

What Are They? Metals that are glasses? Amorphous, or glassy, metals are certainly not transparent, so what does this mean? Here “glass” is used in a technical sense, meaning “a material that has no recognizable structure,” latinized to “amorphous.” That may not sound remarkable but it is – indeed such materials did not exist before 1960, when the first tiny sliver was made by rapidly cooling (“quenching”) a complex alloy of gold at an incredible rate of 1,000,000 C/sec. That does not suggest much promise for the large-scale production of bulk materials, but such has been the pace of alloy development that you can now buy golf clubs with amorphous metal heads.

When metals are cast, crystals nucleate in the coldest part of the mold and grow inwards until they meet, giving a solid casting made up of a large number of interlocking crystals or grains. Most metals, as liquids, are very fluid – about as runny as water – meaning that atoms can rearrange easily and quickly. As a crystal grows into the liquid, atoms joining it have sufficient mobility that each seeks the spot where it fits best, and that automatically extends the ordered crystal. But if the alloy has many components of different size and affinity, it becomes much more viscous when liquid – more like honey than water – and the atoms in it have less mobility. Further, this affinity between the different components of the alloy causes clusters to form in the liquid and these do not easily rearrange to join the growing crystal. All this means that if the alloy is cooled fast, limiting the time for possible rearrangements, the liquid simply goes solid without crystallization.

Design Notes New alloys based on zirconium, titanium, iron, and magnesium, alloyed with many other components, form glasses at easily achievable cooling rates, opening up commercial exploitation of amorphous metals. They are, at present, expensive (about \$18/lb or more) but their properties, even at that price, are enticing. They are very hard and they have very high strength, stronger, for the same weight, than titanium alloys. They can be molded by molding techniques, giving process routes that are not available for conventional metals. They have excellent corrosion resistance. And they can be sprayed to give coatings that have the same properties.

Potential Uses Glassy metals are exceptionally hard, extremely corrosion resistant, and they have the combination of properties which makes them better than any other metals for springs, snap together parts, knife-edges, strong, light casings, and other applications in which high strength in thin sections is essential. Their process ability, too, is exceptional, allowing them to be molded to complex shapes.

Competing Materials Titanium alloys, high-strength steels.

The Environment Some glassy metals contain beryllium, making disposal a problem; rapid progress in alloy development can be expected to deliver materials that have no toxic ingredients.

Suppliers Howmet Research Corporation Inc., www.howmet.com; Liquid metal Technologies, www.liquidmetal.com.

Others

Attributes of Ti-based Metal

Price, \$/kg	32.00–40.00
Density, Mg/m ³	6.2–6.4

Technical Attributes

El. modulus, GPa	91–100
Elongation, %	1.9–2.1
Fr. toughness, MPa·m ^{1/2}	52–57
Vickers hardness, H _v	555–664
Yield strength, MPa	1800–2000

Eco-Attributes

Energy content, MJ/kg	350–400
Carbon footprint, CO ₂ (kg/kg)	7.5
Recycle potential	High

Aesthetic Attributes

Reflectivity, %	95–99
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Features (Relative to Other Metals)

- Exceptionally resilient
- Exceptionally wear resistant
- Corrosion resistant

Shape-memory Alloys

What Are They? Shape-memory alloys (SMAs) are a group of metals that have the remarkable ability to return to some previously defined shape when heated. Some exhibit shape memory only upon heating (one-way shape memory); others undergo a change in shape upon re-cooling (two-way shape memory). They work by having a crystal structure called thermo-elastic martensite: this allows the alloy to be deformed by a twinning mechanism below the transformation temperature. The deformation is reversed when the structure reverts to the parent phase on heating.

The principal commercial grades are the NiTi alloys and the copper-based CuZnAl and CuAlNi alloys. The NiTi alloys have greater shape-memory strain (up to 8% versus 4–5% for the copper-based alloys), can generate stresses as high as 700 MPa and have excellent corrosion resistance, important in biomedical applications. The copper-based alloys are less corrosion resistant and are susceptible to stress-corrosion – cracking – but they are much less expensive. The transformation temperature can be adjusted between –200 and 110 °C by tweaking the alloy composition. The maximum transformation strain is 8% for single use; for 100 cycles it is 6%; for 100,000 cycles it falls to 4%.

Design Notes In free recovery devices a SMA component is deformed while martensitic, and the only function required of the shape memory is that the component return to its previous shape (while doing minimal work) on heating. An application of this is the NiTi blood-clot filter – a wire that is shaped to anchor itself in a vein and catch passing clots. The part is chilled so it can be collapsed and inserted into the vein, then body heat is sufficient to turn the part to its functional shape.

In constrained recovery devices the SMA part is required to exert a force. An example is the hydraulic coupling manufactured as a cylindrical sleeve slightly smaller than the metal tubing it is to join. The sleeve diameter is expanded while martensitic, and, on warming to austenite, it shrinks in diameter and clamps the tube ends.

In force-actuators applications, the shape-memory component is designed to exert force over a considerable range of motion, often for many cycles. An example is a fire safety valve, which incorporates a CuZnAl actuator designed to shut off toxic or flammable gas flow when fire occurs.

Proportional control applications use only a part of the shape recovery to accurately position a mechanism, exploiting the fact that the transformation occurs over a range of temperatures.

In super-elastic applications an SMA alloy is designed to be above its transformation temperature at room temperature. This allows it to be deformed heavily, yet immediately recover its original shape on unloading, so that it appears to be elastic, as in super-elastic NiTi eyeglass frames.

Potential Uses The properties of the NiTi alloys, particularly, suggest increasing use in bio medical applications. They are extremely corrosion resistant and bio-compatible, can be fabricated into the very small sizes, and have properties of elasticity and force delivery that allow applications not possible any other way.

Suppliers Shape-Memory Applications, Inc., www.sma-inc.com.



Attributes of Nitinol, NiTi Alloy

Density, mg/m³ 6.42–6.47

Technical Attributes

El. modulus, GPa 8–83

Elongation, % 5–25

Yield strength, MPa 195–690

Th. conduct., W/m·K 17–18

Th. expansion, 10^{–6}/K 10.5–11.5

Eco-Attributes

Energy content, MJ/kg 320–380

Carbon footprint, CO₂ (kg/kg) 23

Recycle potential High

Aesthetic Attributes

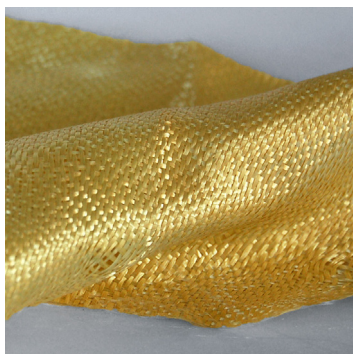
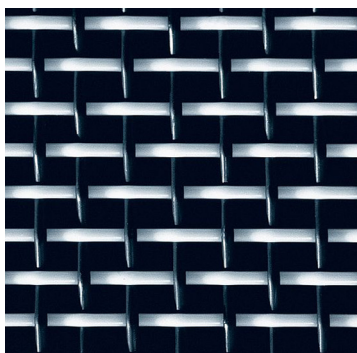
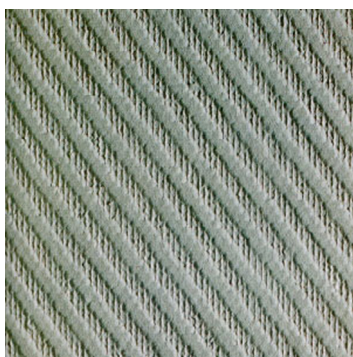
Reflectivity, % 80–90

Features (Relative to Other Metals)

Ability to actuate

Corrosion resistant

Electrically conductive

**Aramid Fibers****Carbon Fibers****Glass Fibers**

Technical Fibers

Aramid Fibers

What Are They? Originally produced by Dupont as Kevlar, aramid fibers are processed in such a way that the polymer chains are aligned parallel to the axis of the fiber. The chemical unit is an aromatic polyamide with a ring structure that gives high stiffness; the strong covalent bonding gives high strength. They are available in low density/high strength form (Kevlar 29), as high modulus fibers (Kevlar 49), and as ultra high modulus fibers (Kevlar 149). The first is used in ropes, cables, and armor; the second as reinforcement in polymers for aerospace, marine, and automotive components. Nomex fibers have excellent flame and abrasion resistance; they are made into a paper that is used to make honeycomb structures. These materials are exceptionally stable and have good strength, toughness, and stiffness up to 170°C. This record describes the properties of single Kevlar 49 aramid fibers.

Typical Uses As woven cloth: body armor protective clothing, bomb/projectile protection, and, with boron carbide ceramic, bullet-proof vests. As paper: honeycomb cores for sandwich panels. As fibers and weaves: as reinforcement in polymer composites.

Carbon Fibers

What Are They? Carbon fibers are made by pyrolyzing organic fibers such as viscose, rayon, or polyacrylonitrile (PAN), or from petroleum pitch. The PAN type has the better mechanical properties, but those produced from pitch are cheaper. PAN fibers are first stretched for alignment, then oxidized in air at slightly elevated temperatures, then carbonized in an inert environment at very high temperatures, and finally heated under tension to convert the crystal structure to that of graphite. Carbon fibers have high strength and stiffness with low density, but they oxidize at high temperatures unless the atmosphere is reducing. They come in four grades: high modulus, high strength, ultra high modulus, and ultra high strength – with cost increasing in that order. The single fibers are very thin (<10 microns in diameter); they are generally spun into tows and woven into textiles. They are primarily used as reinforcement in polymer, metal, or carbon matrices. This record describes the properties of single high strength (HS) carbon fibers.

Typical Uses CFRP, and metal-matrix and ceramic matrix composites. Carbon fiber-reinforced carbon for brake pads in racing cars and aircraft.

Glass Fibers

What Are They? Glass fibers are made by drawing molten glass through a spinner, giving continuous fibers of diameter between 10 and 100 microns. Their perfection gives them exceptional strength in tension, yet they are flexible. They can be aggregated into loose felt that has very low heat conduction. Therefore it is used in an array of thermal insulation products for buildings; most commonly in a loose mat form. They can be woven into a fabric, and printed or colored to give a fire-resistant substitute for curtains or covers (when the woven fabric is treated with silicone it can be used up to 250°C). As chopped strand or as continuous fibers or yarns (bundles of fibers), they form the reinforcement in glass fiber reinforced polymers, GFRPs. There are several grades of glass fiber, differing in composition and strength. E-glass is the standard reinforcement. C-glass has better corrosion resistance than E; R and S have better mechanical properties than E but are more expensive. AR-glass resists alkalis, allowing it to be used to reinforce cement.

Typical Uses Glass fiber is used for thermal insulation, fire-resistant fabric, reinforcement of polymers to make GFRP. E-glass is formulated specifically for reinforcing polymers.

Aramid, Carbon, Glass, continued

Attributes of Aramid, Carbon, Glass

	Aramid	Carbon	Glass (e-Glass)
Price, \$/kg	70.30-198.00	40-50	1.63-3.226
Density, Mg/m ³	1.44-1.45	1.80-1.84	2.5-2.6

Technical Attributes

El. modulus, GPa	125-135	225-260	72-85
Elongation, %	2.7-2.9	0	0
Yld. strength, MPa	2250-2750	3750-4000	1900-2050
Service temp., C	200-300	530-580	347-377
Specific heat, J/kg·K	1350-1450	705-715	800-805
Th. conduct., W/m·K	0.2-0.3	80-200	1.20-1.35
Th. expansion, 10 ⁻⁶ /K	(-4)-(-2)	0.2-0.4	4.9-5.1

Eco-Attributes

Energy content, MJ/kg	1110-1230	380-420	62.2-68.8
Carbon footprint, CO ₂ (kg/kg) 3.6	17	25	3.5
Recycle potential	Low	Low	Low

**Coir Fibers**

Natural Fibers

Coir Fibers

What Are They? Coir (from Malayalam kayar, cord) is a coarse fiber extracted from the fibrous outer shell of a coconut. The individual fiber cells are narrow and hollow, with thick walls made of cellulose. They are pale when immature but later become hardened and yellowed as a layer of lignin is deposited on their walls. There are two varieties of coir. White coir is harvested from the coconuts before they are ripe. The fibers are white or light brown in color and are smooth and fine. They are generally spun to make yarn that is used in mats or rope. Brown coir is harvested from fully ripened coconuts. It is thicker, stronger and has greater abrasion resistance than white coir. It is typically used in mats, brushes, and sacking. The coir fiber is relatively waterproof and is one of the few natural fibers resistant to damage by salt water. Both modulus and tensile strength depend strongly on the type of fiber (bundle or single filament) and moisture content.

Typical Uses White coir is in used in rope making and, when woven, for matting. White coir also used to make fishing nets due to its excellent resistance to salt water. Brown coir is used in floor mats and doormats, brushes, mattresses, floor tiles and sacking, and twine. Pads of brown coir pads are sprayed with rubber latex, which bonds the fibers together (rubberized coir); it is used as upholstery padding in the automobile industry.

**Cotton Fibers**

Cotton Fibers

What Are They? Cotton is fiber from the blossom of the plant *Gossypium*, grown in hot climates. There are many species; all are roughly 95% cellulose, with a little wax. Fiber length and fineness determine quality. Cotton is used to make a vast range of different fabrics: sailcloth, canvas, voile, calico, gingham, muslin, crepe, cambic, olrgandy, crinoline, twill, and damask. They differ in the quality of the fiber and the nature of the weave. This record gives data for single cotton fibers. The properties of fabrics made from it depend strongly on the weave.

Typical Uses Fabric and ropes, bandages, textiles, reinforcing mesh.

**Glass Fibers**

Flax Fibers

What Are They? Flax is a bast-derived fiber from the stalk of the linseed plant (*Linum usitatissimum*). As with hemp, the fibers are freed from the stalk by an open-air retting process of an exceptionally smelly kind. (Many of those that have to put up with it live in Belgium and Ireland, two major producers.) It is used to make linen and rope, all highly valued for their strength and durability. Linen coverings and wall hangings were widely used in the 19th century for internal surfaces in grand houses. Flax, like hemp, kenaf, ramie, and jute belongs to the family of bast plants, known for their long, tough fibers. Bast plants have an outer stem layer that contains 10–40% of the stronger fibrous mass of the stem in fiber bundles surrounding a less strong inner fibrous material.

Typical Uses Fabric and ropes, floor coverings, interior textiles, and furniture upholstery. Flax has been used as a reinforcement polymer-matrix composites for natural fiber rein forced concrete. It demonstrates good stability in the cured concrete while lending the composite a measure of strength. However, steel reinforcing is still necessary.

Coir, Cotton, Flax, Continued
Attributes of Coir, Cotton, Flax

	Coir	Cotton	Flax
Price, \$/kg	0.25–0.50	2.10–4.20	2.10–4.20
Density, Mg/m ³	1.15–1.22	1.52–1.56	1.42–1.52

Technical Attributes

El. modulus, GPa	4–6	7–12	75–90
Elongation, %	15–35	5–12	1.2–1.8
Yld. strength, MPa	100–150	100–350	150–338
Specific heat, J/kg·K		1200–1230	1220–1420
Th. conduct., W/m·K		0.57–0.61	0.25–0.30
Th. expansion, 10 ^{−6} /K	37.4–49.3	15–30	15–30

Eco-Attributes

Energy content, MJ/kg	7.20–7.96	44–48	10–12
Carbon footprint, CO ₂ (kg/kg) 3.6	0.5	2.6	0.4
Recycle potential	Low	Low	Low



Hemp Fibers

Natural Fibers

Hemp Fibers

What Are They? Hemp is a fiber derived from the stalk of the weed *Cannabis Sativa*. Its chemistry is almost the same as cotton but its fibers are coarser and stronger. The fibers are freed from the stalk by a retting process remarkable for the unpleasant smells it creates. This record gives data for single hemp fibers. The properties of fabrics made from it depend strongly on the weave.

Typical Uses Rope; coarse fabric.

Jute Fibers

What Are They? Jute is a long, soft, shiny vegetable fiber made from plants in the genus *Corchorus*, family Malvaceae. Like kenaf, industrial hemp, flax (linen) and ramie, jute is a bast fiber plant, one in which the fibers extracted from the stem or bast. Jute is one of the cheapest natural fibers and is second only to cotton in amount produced and variety of uses. It can be spun into coarse, strong threads. When woven it is called hessian or burlap. There is growing interest in using jute as reinforcement in composites, replacing glass.

Typical Uses Jute is used chiefly to make cloth for wrapping bales of raw cotton, and to make sacks and coarse cloth. The fibers are also woven into curtains, chair coverings, car pets, area rugs, hessian cloth, and backing for linoleum.

Kenaf Fibers

What Are They? Kenaf (*Hibiscus cannabinus*) is a fast-growing fiber crop related to cotton, okra, and hibiscus. The plants, which reach heights of 8–20 feet, are harvested for their stalks from which the fiber is extracted. The fiber is used in the manufacture of industrial textiles, ropes, and twines. Kenaf is among the most widely utilized of the bast (stem) fibers.

Typical Uses The main uses of kenaf fiber have been rope, twine, coarse cloth (similar to that made from jute), and paper. Emerging uses of kenaf fiber include engineered wood, insulation, and clothing-grade cloth and as a reinforcement in polymer-matrix composites.

Hemp, Jute, Kenaf, continued
Attributes of Hemp, Jute, Kenaf

	Hemp	Jute	Kenaf
Price, \$/kg	1.00–2.10	0.35–1.50	0.26–0.52
Density, Mg/m ³	1.47–1.52	1.44–1.52	1.44–1.50

Technical Attributes

El. modulus, GPa	55–70	35–60	60–66
Elongation, %	1.4–1.7	1.7–2.0	1.3–5.5
Yld. strength, MPa	200–400	145–530	195–666
Specific heat, J/kg·K	1200–1220	1200–1220	1200–1220
Th. conduct., W/m·K	0.25–0.30	0.25–0.35	0.25–0.35
Th. expansion, 10 ^{–6} /K	15–30	15–30	15–30

Eco-Attributes

Energy content, MJ/kg	9.5–10.5	30–33	31–34
Carbon footprint, CO ₂ (kg/kg) 3.6	1.2	1.3	1.3
Recycle potential	Low	Low	Low



Natural Fibers

Ramie Fibers

What Are They? Ramie (*Boehmeria nivea*) is a flowering plant in the nettle family. Ramie is one of the oldest fiber crops, used for at least six thousand years, used for cordage and fabric production. Like jute, hemp, flax (linen) and ramie, ramie is a bast fiber plant, one in which the fibers extracted from the stem or bast. It is one of the strongest natural fibers.

Typical Uses Ramie is used to make industrial sewing thread, packing materials, fishing nets, and filter cloths. It is also made into fabrics for household furnishings (upholstery, canvas) and clothing, frequently in blends with other textile fibers. Shorter fibers and waste are used in paper manufacture.

Sisal Fibers

What Are They? Sisal fiber is derived from an agave, *Agave sisalana*. Sisal is valued for cord age use because of its strength, durability, ability to stretch, affinity for certain dyestuffs, and resistance to deterioration in saltwater.

Typical Uses Sisal is used by industry in three grades, according to www.sisal.ws. The lower grade fiber is processed by the paper industry because of its high content of cellulose and hemicelluloses. The medium grade fiber is used in the cordage industry for making: ropes, baler and binders twine. Ropes and twines are widely employed for marine, agricultural, and general industrial use. The higher-grade fiber after treatment is converted into yarns and used by the carpet industry. Sisal is now used as a reinforcement in polymer-matrix composites.

Wool Fibers

What Are They? Wool is the hair or fleece of the sheep, alpaca, rabbit (angora), camel (camel hair) certain goats (mohair, Kashmir) and llamas (vicuna). It remains, even today, an important commercial fiber because of its hard wearing qualities (as in wool carpets), the remarkable thermal insulation that it offers (as in woolen sweaters) and, at its best, its high quality (as in lambs wool, mohair and vicuna). It is widely used for carpets, seat covers, clothing and blankets. Wool is keratin. Its fibers have crimps or curls which create pockets that insulate and gives the wool a spongy feel. The outside surface of the fiber consists of a series of serrated scales that overlap each other much like the scales of a fish, making it possible for the fibers to cling together and produce felt. (The same serrations cling together when wool is improperly washed and shrinks; it will only return to its original position after being stretched. Its unique properties allow shaping and tailoring, making the wool the most popular fabric for tailoring fine garments. It is woven in many different ways to give cloth, tweed, plaid, flannel, or worsted. Wool fabrics are dirt resistant, flame resistant, and, in many weaves, resists wear, and tearing.

Typical Uses Clothing, carpets, upholstery fabrics, curtains, blankets, and insulation wool.

Attributes of Ramie, Sisal, Wool

	Ramie	Sisal	Wool
Price, \$/kg	1.50–2.50	0.60–0.70	2.10–4.20
Density, Mg/m ³	1.45–1.55	1.40–1.45	1.25–1.34

Technical Attributes

El. modulus, GPa	38–44	10–25	3.8–4.2
Elongation, %	2.0–2.2	4–6	35–55
Yld. strength, MPa	45–330	495–711	70–115
Service temp., C	127–147	127–147	
Specific heat, J/kg·K	1200–1220	1200–1220	1320–1380
Th. conduct., W/m·K	0.25–0.35	0.25–0.35	0.19–0.22
Th. expansion, 10 ^{−6} /K	15–30	15–30	15–30

Eco-Attributes

Energy content, MJ/kg	7.2–8.0	7.2–8.0	51–56
Carbon footprint, CO ₂ (kg/kg)	3.6	0.5	0.5–3.4
Recycle potential	Low	Low	Low

Shaping Profiles

Shaping processes give form to materials. The choice of process depends on the material, on the shape, on the required size, precision and surface finish; and the associated cost depends, most critically, on the number of components to be made – the batch size.

There are a number of broad families of shaping process, suggested by the index on the facing page. Some are economic even when the batch size is small: vacuum forming of polymers and sand-casting of metals are examples. Others become economic only when a large number is made: injection molding of polymers and die casting of metals, for instance. Variants of each process are adapted to be economic at a chosen range of batch size; and special processes have been developed that are viable for prototyping – a batch size of one. This and certain other attributes of a process are readily quantified: the size of the components it can make; the minimum thickness of section it allows; the precision of dimensions (“allowable tolerance”); the roughness or smoothness of the surface. One, however, is not easy to quantify: that of shape. Wire drawing makes only one shape: a cylinder. Investment casting makes shapes of unlimited complexity: hollow, reentrant, multi-connected. There have been many attempts to classify shape, none completely successful. In these profiles we will refer to a simple set of shapes; each is illustrated in the figure on the first text page.

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
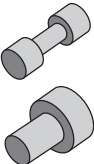



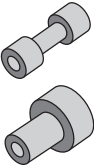
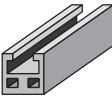
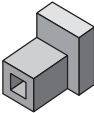
Other




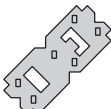

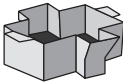

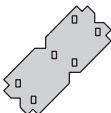
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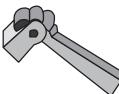

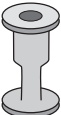
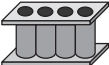


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Generic Shapes
A set of possible shapes common in product design.

Prismatic	CIRCULAR		NON-CIRCULAR	
	SOLID		HOLLOW	
	 <i>Plain</i>		 <i>Stepped</i>	
	 <i>Plain</i>		 <i>Stepped</i>	
	 <i>Plain</i>		 <i>Stepped</i>	
	 <i>Plain</i>		 <i>Stepped</i>	

Thin- Walled	CURVED			FLAT
	AXISYMMETRIC			
	 <i>Shallow</i>	 <i>Deep</i>	 <i>Deep, re-entrant</i>	 <i>Cutouts</i>
	 <i>Shallow</i>	 <i>Deep</i>	 <i>Deep, re-entrant</i>	 <i>No Cutouts</i>

Bulk	PARALLEL FEATURES		TRANSVERSE FEATURES	
	SOLID		HOLLOW	
	 <i>Simple</i>	 <i>Complex</i>	 <i>Simple</i>	 <i>Complex</i>
	 <i>Simple</i>	 <i>Complex</i>	 <i>Simple</i>	 <i>Complex</i>

Further reading

ASM (1962) "Casting Design Handbook," Materials Park, OH, USA. (Old, but still a useful resource.)

Bralla, J.G. (1998) "Handbook of Product Design for Manufacture," second edition, McGraw-Hill, NY, USA. ISBN 0-07-007139-X. (The Bible – a massive compilation of information about manufacturing processes, authored by experts from different fields, and compiled by Bralla. A handbook rather than a teaching text – not an easy read.)

Clegg, A.J. (1991) "Precision Casting Processes," Pergamon Press, Oxford, UK. ISBN 0-08-037879-X. (Descriptions and capabilities of the principal casting production processes.)

DeGarmo, E.P., Black, J.T. and Kohser, R.A. (1984) "Materials and Processes in Manufacturing," Macmillan Publishing Company, New York, NY, USA. ISBN 0-471-29769-0. (A comprehensive text focusing on manufacturing processes, with a brief introduction to materials. The perspective is that of metal processing; the processing of polymers, ceramics, and glasses gets much briefer treatment.)

Edwards, L. and Endean, M., (Eds.) (1990) "Manufacturing with Materials," Materials in Action Series," The Open University, Butterworths, London. ISBN 0-408-02770-3. (A teaching text on material shaping and joining, nicely illustrated by case studies.)

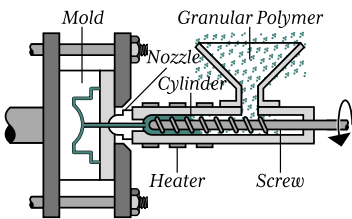
Kalpakjian, S. (1984) "Manufacturing Processes for Engineering Materials," Addison-Wesley, Reading, MA, USA. ISBN 0-201-11690-1. (A comprehensive and widely used text on manufacturing processes for all classes of materials.)

Lesko, J. (1999) "Materials and Manufacturing Guide: Industrial Design," John Wiley & Sons, New York, NY. ISBN 0-471-29769-0. (Brief descriptions, drawings, and photographs of materials and manufacturing processes, with useful matrices of characteristics, written by a consultant with many years of experience of industrial design.)

Mayer, R.M. (1993) "Design with Reinforced Plastics," The Design Council and Bourne Press Ltd., London, UK. ISBN 0-85072-294-2. (A text aimed at engineers who wish to design with fiber-reinforced plastics; a useful source of information for shaping processes for polymer composites.)

Swift, K. and Booker, J.D. (1998) "Process Selection: From Design to Manufacture," John Wiley & Sons, UK. ISBN 0-340-69249-9. (Datasheets in standard formats for 48 processes, some of which are for shaping.)

Injection Molding



Attributes of Injection Molding

Weight range, kg	0.01–25
Minimum thickness, mm	0.3–10
Shape complexity	High
Allowable tolerance, mm	0.05–1
Surface roughness, μm	0.2–1.6
Economic batch size	10K–1000K

What Is It? No other process has changed product design more than injection molding. Injection molded products appear in every sector of product design: consumer products, business, industrial, computers, communication, medical and research products, toys, cosmetic packaging, and sports equipment. The most common equipment for molding thermoplastics is the reciprocating screw machine, shown schematically in the figure. Polymer granules are fed into a spiral press where they mix and soften to a dough-like consistency that can be forced through one or more channels (“sprues”) into the die. The polymer solidifies under pressure and the component is then ejected. Thermoplastics, thermosets and elastomers can all be injection molded. Co-injection allows molding of components with different materials, colors, and features. Injection foam molding allows economical production of large molded components by using inert gas or chemical blowing agents to make components that have a solid skin and a cellular inner structure.

Shapes Simple and complex solid bulk shapes.

Design Notes Injection molding is the best way to mass-produce small, precise, polymer components with complex shapes. The surface finish is good; texture and pattern can be easily altered in the tool, and fine detail reproduces well. Decorative labels can be molded onto the surface of the component (see In-mold Decoration). The only finishing operation is the removal of the sprue.

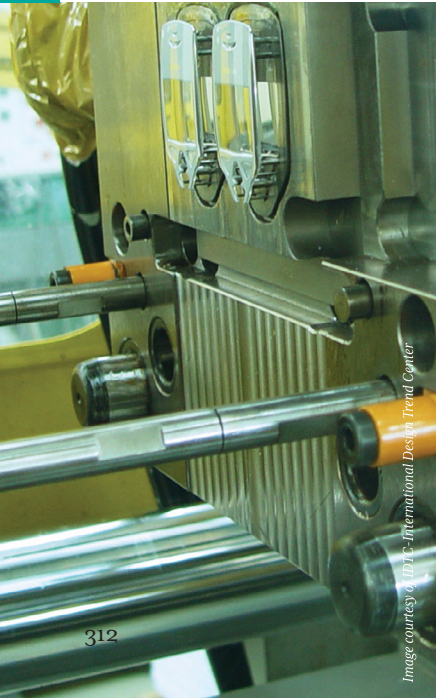
Technical Notes Most thermoplastics can be injection molded, although those with high melting temperatures (e.g. PTFE) are difficult. Thermo-plastic based composites (short fiber and particulate filled) can be processed providing the filler-loading is not too large. Large changes in section area are not recommended. Small re-entrant angles and complex shapes are possible, though some features (e.g. undercuts, screw threads, inserts) may result in increased tooling costs. The process may also be used with thermosets and elastomers.

The Economics Capital costs are medium to high, tooling costs are usually high – making injection molding economic only for large batch sizes. Production rate can be high particularly for small moldings. Multi-cavity molds are often used. Prototype moldings can be made using single cavity molds of cheaper materials.

Typical Products Housings, containers, covers, knobs, tool handles, plumbing fittings, lenses, toys, and models.

The Environment Thermoplastic sprues can be recycled. Extraction may be required for volatile fumes. Significant dust exposures may occur in the formulation of the resins. Thermostatic controller malfunctions can be hazardous.

Competing Processes Polymer casting, die-casting of metals.



Rotational Molding

What Is It? The chunky, brightly-colored chairs for children are examples of what can be done with rotational molding. A pre-measured quantity of polymer powder is fed into a cold die, which is then heated in a large oven while it is rotated about two axes simultaneously. This tumbles and melts the powder, coating the inside walls of the mold to a thickness set by the initial load of powder, creating a hollow shell. The component then cools in a dwell cycle, the mold chilled by air or water spray. The process is best suited for components that are large, hollow, and closed; although small, thin-walled components can be made and open shapes can be created by subsequent machining.

Shapes Simple, closed, hollow thin-walled shapes.

Design Notes Rotational molding is versatile and one of the few processes able to make hollow (and thus material-efficient) shapes. The low pressure limits the possible sharpness of detail, favoring rounded forms without finely-detailed moldings. Inserts and pre-formed sections of different color or material can be molded in, allowing scope for creativity. Components with large openings – trash cans and road cones, for example – are molded in pairs and separated by cutting.

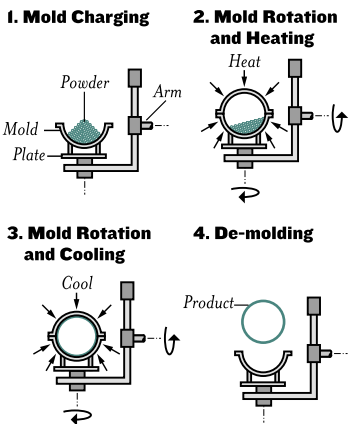
Technical notes In principle, most thermoplastics can be rotationally molded, though in normal practice the range is more restricted – the most common is polyethylene. The process makes large components, but the thickness is limited by the thermal conductivity of the polymer, since it has to melt through this thickness. One advantage: it produces virtually stress-free components. It is possible (but difficult) to vary the wall thickness; abrupt changes of section are not possible. Because of the two axes rotation, component length is restricted to less than four times the diameter. Thermosets can now be rotationally molded too – polyurethane is the most usual.

The Economics Equipment and tooling costs are low – much lower than for injection molding – but cycle times are longer than any other molding process, and it is labor intensive.

Typical Products Tanks, food and shipping containers, housings, portable lavatories, traffic cones, large toys, trashcans, buckets, boat hulls, pallets.

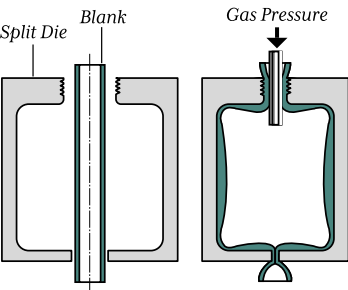
The Environment No problems here.

Competing Processes Thermoforming; blow molding; lay-up methods.



Attributes of Rotational Molding	
Weight range, kg	0.1–50
Minimum thickness, mm	2.5–6
Shape complexity	Low
Allowable tolerance, mm	0.4–1
Surface roughness, μm	0.5–2
Economic batch size	100–10K

Blow Molding



Attributes of Blow Molding

Weight range, kg	0.001–0.3
Minimum thickness, mm	0.4–3
Shape complexity	Low
Allowable tolerance, mm	0.25–1
Surface roughness, μm	0.2–1.6
Economic batch size	1K–10,000K

What Is It? Blow molding is glass blowing technology adapted to polymers. In extrusion blow molding a tube or parison is extruded and clamped in a split mold with a hollow mandrel at one end. Hot air is forced under pressure through the mandrel, blowing the polymer against the mold walls where it cools and freezes. In injection blow molding, a preform is injection molded over a mandrel and transferred to the blowing die. Air is injected under pressure through the mandrel blowing the polymer against the mold walls where it cools and freezes, as before. The process gives better control over finished component weight and wall thickness than extrusion blow molding, with better precision in the unblown, injection molded neck areas, lending itself to screw closures, etc. Solid handles can be molded in. In stretch blow molding, an important variant, the temperature is chosen such that the polymer is drawn as it expands, orienting the molecules in the plane of the surface. It is used in the production of PET drink bottles.

Shapes Large, hollow thin-walled shapes.

Design Notes Extrusion blow molding allows a wide variety of hollow shapes to be formed, offering channels for air or liquid. Multi-layer injection blow molding is more commonly used for components that need to be gas tight and strong; here barrier layers are added to prevent gas diffusion and the outer layers to provide strength, impact resistance, and good acceptance of printing and decoration. Insert molding is possible.

Technical Notes Blow molding is limited to thermoplastics, commonly PET, PC, HDPE, LDPE, PP, ABS, and some PVCs. Limited levels of reinforcement are possible for composite materials. The wall thickness should be as uniform as possible to avoid distortion.

The Economics Extrusion blow molding is the cheaper of the two processes, because the die costs are less. It is competitive for large containers (capacity above 0.5 liters) and high batch sizes. Tooling costs for extrusion blow molding are much higher, limiting the process to volume production.

Typical Products Injection blow molding: bottles and containers, particularly those with threaded closures. Extrusion blow molding: containers, cases for tools and portable machinery, and large hollow structures such as car bumpers.

The Environment Waste material can be recycled. The resins can generate dust and vapors, requiring good ventilation.

Competing Processes Rotational molding.

Expanded Foam Molding

What Is It? The snow-white, crisp, light protective packaging in which your computer arrived, and which you discarded, oblivious of its visual aesthetics, was made by expanded foam molding of polystyrene. It is a low temperature, low pressure, process using cheap mold materials, with uses far beyond those of throwaway packaging. There are two stages in its operation. Solid polymer granules, colored, if desired, containing a foaming agent that releases CO₂ on heating (a commodity product, widely available) are first softened and expanded by steam-heating under a small pressure. The softened particles are transferred to aluminum molds (to give good heat transfer) and steam-heated at 3 atmospheres, causing them to expand to 20 or more times their original volume and fuse together, filling the mold and taking up its shape.

Shape Three-dimensional solid shapes.

Design Notes Expanded foam moldings acquire a smooth skin where they contact the mold surface, and accept detail provided the radii are greater than 2 mm. The product is very cheap, gives good impact protection, and can be recycled – so as packaging goes it is attractive. It is exceptionally good as a thermal insulator – hence its use in disposable cups and cooler bags and walls for kitchen refrigerators, refrigerated trucks, and storage buildings. Increasingly, designers see other possibilities: expanded bead moldings have interesting acoustic properties, complex profiles can be molded, the material is very light and has visual and tactile properties that are interesting. But the products are very easily damaged.

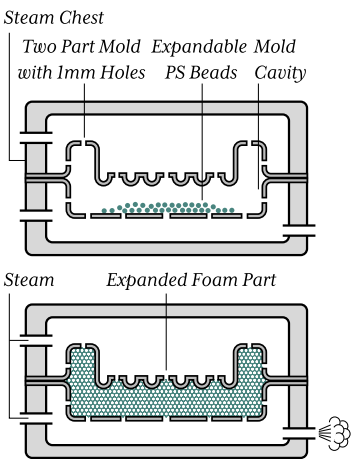
Technical Notes Thermoplastics are easy to mold, polystyrene particularly so. Expanded foam molding gives a closed cell foam with a porosity of 80–95%. The high porosity and closed cells make it a good thermal insulator; the low density (about 10% that of water) gives it outstanding buoyancy.

The Economics The low molding pressure and temperature makes this a particularly cheap process – hence its wide use in disposal, apparently valueless, objects.

Typical Products Disposable packaging for drinks and food (McDonalds has been held to ransom for this), lifesaving equipment, water-sport products like surfboards and life vests; thermal insulation in coolers, containers, and carriers, core materials for sandwich structures (window and door frames, floor panels), protection of valuable products such as electronic, computer, or audio systems.

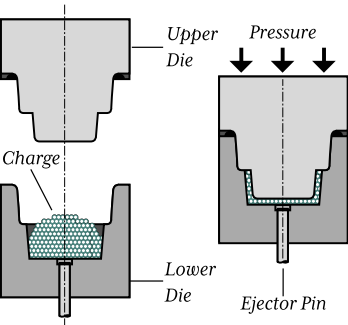
The Environment At one time, CFC blowing agents were used for polystyrene expansion. These have now been replaced by gases that – in the volume in which they are used – do not damage the environment.

Competing Processes Nothing else is quite as cheap.



Attributes of Expanded Foam Molding

Weight range, kg	0.01–10
Minimum thickness, mm	5–100
Shape complexity	Low/Med
Allowable tolerance, mm	0.5–2
Surface roughness, μm	50–500
Economic batch size	2K–1000K



Attributes of Polymer Molding

Weight range, kg	0.2–20
Minimum thickness, mm	1.5–25
Shape complexity	Low/Med
Allowable tolerance, mm	0.1–1
Surface roughness, μm	0.2–2
Economic batch size	2K–200K

Attributes of BMC and SMC Molding

Weight range, kg	0.3–60
Minimum thickness, mm	1.5–25
Shape complexity	Low/Med
Allowable tolerance, mm	0.1–1
Surface roughness, μm	0.1–1.6
Economic batch size	5K–1000K

Compression Molding

What Is It? In compression molding a pre-measured quantity of polymer – usually a thermoset – in the form of granules or a pre-formed tablet containing resin and hardener is placed in a heated mold. The mold is closed creating sufficient pressure to force the polymer into the mold cavity. The polymer is allowed to cure, the mold is opened, and the component removed. A variant, polymer forging, is used to form thermoplastics that are difficult to mold, such as ultra high molecular weight polyethylene. Compression molding is widely used to shape the composites BMC and SMC.

Shapes Simple bulk shapes (BMC); flat, dished thin-walled shapes (SMC).

Design Notes Compression molding is limited to simple shapes without undercuts. The components generally require some finishing to remove flash. BMC and SMC moldings have good surface finish and accurate dimensioning, good enough for auto manufacturers to use them for external body components. SMC moldings yield high-quality panels and casings; shapes in which the sheet thickness is more or less uniform. BMC moldings yield simple three-dimensional shapes with changes in section.

Technical Notes BMC (bulk molding compound) and SMC (sheet molding compound) differ in the shape and content of reinforcement and filler. BMC has less (15–25% of glass fiber) and it is the easiest to mold to three-dimensional shapes. SMC has more (up to 35%) of glass fiber and is limited to sheet shapes. DMC (dough molding compound) is the genesis – a dough-like mix of thermosetting polyester, polyurethane, or epoxy with hardener, chopped glass fiber, filler, and coloring agent. Two more – GMT (glass mat thermoplastics) and TSC (thermoplastic sheet compounds) – are the thermoplastic equivalent, based on nylon 6 or polypropylene. The word “dough” conveys well the way in which they are shaped: squeezed between a pair of dies, like a pie crust.

The Economics Tooling costs are modest for polymer molding, higher for BMC and SMC molding, making the economic batch size larger for these two.

Typical Products Electrical and electronic components, tableware, washing machine agitators, utensil handles, container caps, appliance housings; SMC: body panels and bumpers for cars and trucks, gas and electricity meter boxes, and electrical housings. BMC: more complicated shapes.

The Environment The process itself does not damage the environment, but flash and scrap cannot be recycled for thermosets.

Competing Processes Injection molding; resin transfer molding; lay-up methods.

Resin Transfer Molding

What Is It? Resin transfer molding (RTM) is an easy way of manufacturing complex shapes in fiber-reinforced composites without high tooling costs. It uses a closed mold, in two or more parts, usually made of glass-reinforced polymers or light metal alloys, with injection points and vents to allow air to escape. Reinforcement is cut to shape and placed in the mold, together with any inserts or fittings. The mold is closed and a low viscosity thermo – setting resin (usually polyester) is injected under low pressure through a mixing head in which hardener is blended with the resin. The mold is allowed to cure at room temperature. The fluidity of the resin, and the low molding pressure, give tools a longer life at low cost.

Shapes Simple bulk shapes; shaped panels.

Design Notes Resin transfer molding is increasingly used for large fiber-reinforced polymer components. Shapes can be complex. Ribs, bosses, and inserts are possible. Foam panels can be insert molded to reduce component weight.

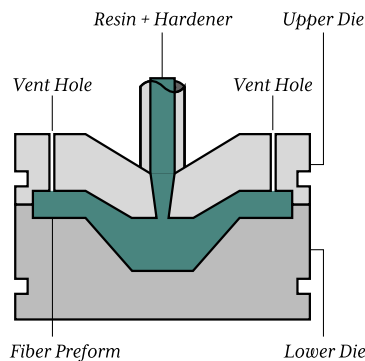
Technical Notes A range of resin systems can be used with RTM: almost any thermosetting resin with a low viscosity is possible, for example, polyester, epoxies, vinyl esters, and phenolics. The reinforcement, typically, is a 25–30% volume fraction of glass or carbon in the form of continuous fiber mat.

The Economics Tooling costs are low, and the process is not particularly labor intensive, making it attractive economically.

Typical Products Manhole covers, compress soil casings, car doors and side panels, propeller blades, boats, canoe paddles, water tanks, bath tubs, roof sections, airplane escape doors.

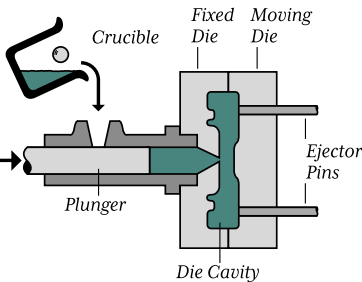
The Environment From the vented, closed mold – with adequate ventilation – it is easy to control emissions, so worker exposure to unpleasant chemicals is drastically reduced, when compared with other composite processes.

Competing Processes Lay-up methods; press molding; BMC and SMC molding.



Attributes of Resin Transfer Molding

Weight range, kg	0.2–20
Minimum thickness, mm	1.5–13
Shape complexity	Med/High
Allowable tolerance, mm	0.25–1
Surface roughness, μm	0.2–1.6
Economic batch size	10K–100K



Attributes of Die-Casting

Weight range, kg	0.05–20
Minimum thickness, mm	1–8
Shape complexity	Med/High
Allowable tolerance, mm	0.15–0.5
Surface roughness, μm	0.5–1.6
Economic batch size	5k–1000k

Die-Casting

What Is It? Most small aluminum, zinc, or magnesium components with a complex shape – camera bodies, housings, the chassis of video recorders – are made by die-casting. It is to metals what injection molding is to polymers, and the two compete directly. In the process, molten metal is injected under high pressure into a metal die through a system of sprues and runners. The pressure is maintained until the component is solid, when the die is opened and the component ejected. For large batch sizes the dies are precision-machined from heat-resistant steel and are water cooled to increase life. For small batch sizes cheaper mold materials are possible.

Shapes Complex bulk shapes; hollow shapes have to be molded in sections and subsequently joined.

Design Notes Pressure die-casting allows thin-walled shapes and excellent surface detail. The integrity of the material properties is less good: turbulent filling of the mold and fast cycle time can lead to shrinkage and porosity. The process can make complex shapes, but elaborate movable cores increase the tooling costs.

Technical Notes Die-casting is widely used to shape aluminum, magnesium, and zinc alloys. Two types of die-casting equipment are commonly used: cold and hot. In the “cold” process, the hot metal is held in a separate container and passed to the pressure chamber only for casting. In the “hot” process the reservoir of hot metal is held in the pressure chamber. The prolonged contact times restrict this process to zinc alloys.

The Economics High tooling costs mean that pressure die-casting becomes economic only for large batch sizes, but the process is one of the few that allows thin-walled castings. Aluminum has a small solubility for iron, limiting die-life to about 100,000 parts. Magnesium has none, giving almost unlimited die-life. Gravity die-casting has lower equipment costs but is usually less economic because the molten metal has to be more fluid – and thus hotter – to fill the mold well, this reduces the production rates.

Typical Products Record player and video player chassis, pulleys and drives, motor frames and cases, switch-gear housings, housings for small appliances and power tools, carburettor and distributor housings, housings for gear-boxes and clutches.

The Environment Aluminum, zinc, and magnesium scrap can all be recycled. The process poses no particular environmental problems.

Competing Processes Investment casting, sand casting; injection molding of polymers.



Sand Casting

What Is It? Sand casting probably started on beaches – every child knows how easy it is to make sand castles. Add a binder and much more complex shapes become possible. And sand is a refractory; even iron can be cast in it. In green sand casting, a mixture of sand and clay is compacted in the split mold around a pattern that has the shape of the desired casting. The pattern is removed to leave the cavity in which the metal is poured. Cheap wooden patterns, with gates and risers attached, are used when the batch size is small and the process is manual, but this is slow and labor intensive. Automated systems use aluminum patterns and automated compaction. In CO_2 /silicate sand casting, a mixture of sand and sodium silicate binder is packed around a pattern as before and flooded with CO_2 to seal the sodium silicate gel. In evaporative sand casting, the pattern is made from polystyrene foam and embedded in sand. When molten metal is poured into the mold, the polystyrene pattern vaporizes. In shell casting, a mixture of fine-grained sand and thermosetting resin is applied to a heated metal pattern (aluminum or cast iron) and cured to form a shell.

Shapes Very complex shapes are possible – think of auto engine blocks.

Design Notes Few processes are as cheap and versatile as sand casting for shaping metals. It allows complex shapes, but the surface is rough and the surface detail is poor. The process has particular advantages for complicated castings with varying section thickness. Bosses, undercuts, inserts, and hollow sections are all practical. Evaporative pattern casting leaves no parting lines, reducing finishing requirements. The minimum wall thickness is typically 3 mm for light alloys, and 6 mm for ferrous alloys.

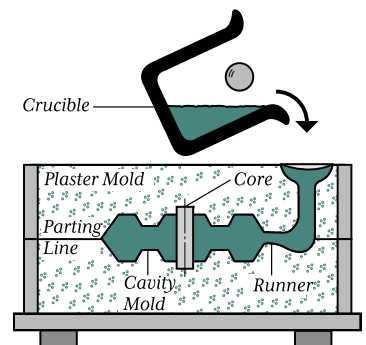
Technical Notes In principle, any non-reactive, non-refractory metal (melting temperature less than 1800 °C) can be sand cast. In particular, aluminum alloys, copper alloys, cast irons, and steels are routinely shaped in this way. Lead, zinc, and tin can be cast in dry sand, but melt at too low a temperature to evaporate the foam pattern in evaporative pattern casting.

The Economics Capital and tooling costs for manual sand casting are low, making the process attractive for small batches. Automated systems are expensive but capable of producing very complex castings.

Typical Products Machine tool frames and bodies, engine blocks and cylinder heads, transmission cases, gear blanks, crank shafts, connecting rods. Evaporative pattern casting: manifolds, heat exchangers, pipe fittings, valve casings, other engine parts.

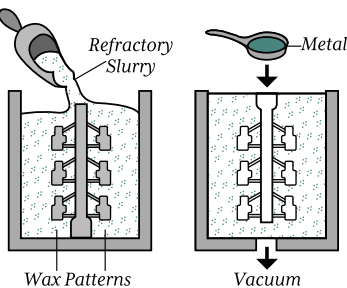
The Environment The mold materials, in many cases, can be reused.

Competing Processes Investment casting; die-casting.



Attributes of Sand Casting

Weight range, kg	0.3–1000
Minimum thickness, mm	5–100
Shape complexity	Med/High
Allowable tolerance, mm	1–3
Surface roughness, μm	12–25
Economic batch size	1–1000K



Attributes of Investment Casting

Weight range, kg	0.001–20
Minimum thickness, mm	1–30
Shape complexity	Med/High
Allowable tolerance, mm	0.1–0.4
Surface roughness, μm	1.6–3.2
Economic batch size	1–50K

Investment Casting

What Is It? If you have gold fillings in your mouth, be thankful for this process – it was used to make them. The lost wax process – the old name for investment casting – has been practiced for at least 3000 years; sophisticated jewelry, ornaments, and icons were being made in Egypt and Greece well before 1500 BC. In investment casting, wax patterns are made and assembled (if small) into a tree with feeding and gating systems. The assembled pattern is dipped into refractory slurry, then covered in refractory stucco and allowed to dry. The procedure is repeated a number of times until about eight layers have built up, creating a ceramic investment shell. The wax is then melted out and the ceramic shell fired before the molten metal is cast. Gravity casting is adequate for simple shapes, but air pressure, vacuum, or centrifugal pressure is needed to give complete filling of the mold when complex, thin sections are involved. The mold is broken up to remove the castings. The process is suitable for most metals of melting temperatures below 2200 C. Because the wax pattern is melted out, the shape can be very complex, with contours, undercuts, bosses, and recesses. Hollow shapes are possible: bronze statues are hollow, and they are made by an elaboration of this process.

Shapes As complex as you like.

Design Notes The process is extremely versatile, allowing great freedom of form. It offers excellent reproduction of detail in small three-dimensional components.

Technical Notes Investment casting is one of the few processes that can be used to cast metals with high melting temperatures to give complex shapes; it can also be used for low melting metals. The traditional uses of investment casting were for the shaping of silver, copper, gold, bronze, pewter, and lead. Today the most significant engineering applications are those for nickel, cobalt, and iron-based alloys to make turbine blades.

The Economics Investment casting lends itself both to small and large batch sizes. For small batch sizes the process is manual, with low capital and tooling costs, but significant labor costs. When automated, the capital costs are high, but quality control and speed are greater. The production rate is increased by the use of multiple molds.

Typical Products Jewelry, dental implants, statuary, metal sculpture and decorative objects, high temperature gas turbines and similar equipment, monumental statues.

The Environment There are the usual hazards associated with casting molten metal, but procedures for dealing with these are routine. The mold materials cannot, at present, be recycled.

Competing Processes Die-casting (for metals that melt below 800 C); sand casting.

Polymer Casting

What Is It? Many resins are sufficiently fluid before polymerization that they can be cast – poured into a shaped mold without applying pressure, where they react and solidify. A few thermoplastics – notably acrylics – and most thermosets can be cast by doing so before they polymerize.

Shapes Most shapes – complex shapes require a flexible mold.

Design Notes The optical properties of cast transparent polymers like acrylics are better than if molded. Fillers can be added, but for this a similar process – centrifugal casting – is frequently used. Large parts and large section thicknesses are common, but the quality of the final part depends heavily on the skill of the operator – trapped air and gas evolution are both potential problems.

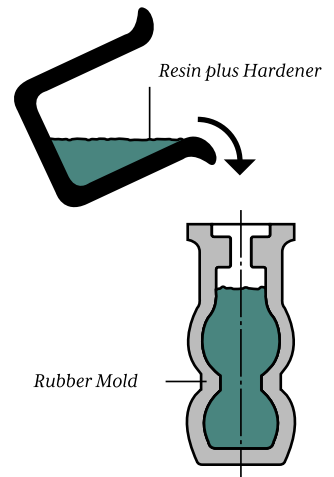
Technical Notes In casting methyl methacrylate (acrylic), a monomer-soluble initiator is used. The reaction is vigorous and liberates much heat that must be dissipated to keep the temperature within safe limits and prevent the monomer from boiling. Considerable shrinkage occurs – as much as 21% for methyl methacrylate – and must be taken into account when designing molds for casting. Using monomer-polymer syrups made by interrupted polymerization helps control both heat and shrinkage.

The Economics The tooling required is cheap; stiff (metal or epoxy) or flexible (elastomer) molds are both possible. For small tooling the price is under \$100, for large tooling it is a few thousand dollars.

Typical Products Elevator buckets, bearings, large gears, sheets, tubes, electronic encapsulation, rod stock, bowling balls, epoxy tooling; centrifugal casting is used for pipes, tanks, and containers.

The Environment Most polymers give off vapors when curing – adequate ventilation is important.

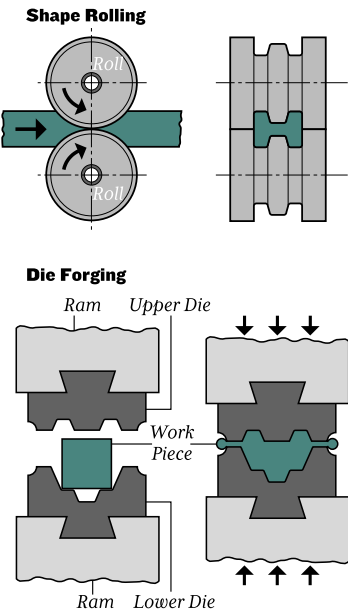
Competing Processes Injection molding, compression molding – but in both cases the dies are much more expensive.



Attributes of Polymer Casting

Weight range, kg	0.1–700
Minimum thickness, mm	2–100
Shape complexity	High
Allowable tolerance, mm	0.8–2
Surface roughness, μm	0.5–1.6
Economic batch size	10–1000

Shape Rolling and Die Forging



What Are They? In rolling and forging a metal ingot is squeezed to shape by massive rolls or dies that subject it to large plastic deformation. Nearly 90% of all steel products are rolled or forged. I-beams and other such continuous sections are made by shape rolling.

In hot rolling, the ingot, heated to about two-thirds of its melting temperature, is forced through a series of rolls that progressively shape the profile. In hot die forging, by contrast, a heated blank is formed between open or closed dies in a single compressive stroke. In cold rolling and forging the metal blank is initially cold, though deformation causes some heating. Often a succession of dies is used to create the final shape.

Shapes Rolling: prismatic shapes only. Forging: Simple solid bulk shapes; re-entrant angles are not possible.

Design Notes The process produces components with particularly good mechanical properties because of the way in which the deformation refines the structure and reduces the porosity. During hot rolling and forging the metal recrystallizes, remaining relatively soft, and its surface may oxidize. Cold rolling and forging, by contrast, impart a high surface finish and cause extreme work-hardening, raising the strength of the product but limiting the extent of deformation.

Technical Notes Most metals can be rolled or forged, but the extent of deformation that is possible varies widely. Those best suited are the range of aluminum and magnesium alloys designed for deformation processing (the “wrought” grades), copper alloys and steels.

The Economics Rolls and dies for rolling and forging have to be made from exceptionally hard materials and are expensive, meaning that shape rolling and closed die forging are suitable only for large batches.

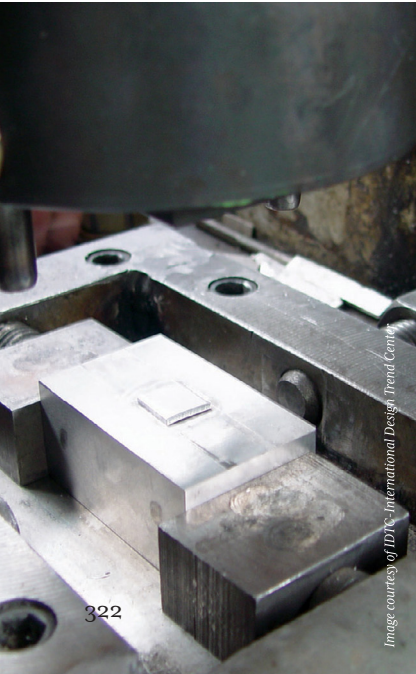
Typical Products Rolling: continuous rods, square sections, I-beams. Forging: highly stressed mechanical parts such as aircraft components, connecting rods, crank shafts, gear blanks, valve bodies, tube and hose bodies, hand and machine tools.

The Environment The lubricants used in rolling and forging generate oil mist and unpleasant vapors, requiring good ventilation.

Competing Processes Extrusion (for continuous prismatic sections); die, sand, or investment casting for solid bulk shapes.

Attributes of Shape Rolling and Die Forging	
Weight range, kg	0.1–100
Minimum thickness, mm	2–100
Shape complexity	Low
Allowable tolerance, mm	0.3–2
Surface roughness, μm	3.2–12.5
Economic batch size	10K–1000K

Bulk Formings



Extrusion

What Is It? The process of squeezing toothpaste from its tube is one of extrusion. The gooey toothpaste – or the gooey polymer or metal in the industrial process – is forced by pressure to flow through a shaped die, taking up the profile of the die orifice. In co-extrusion two materials are extruded at the same time and bond together – a trick used in toothpaste to create colored stripes in it.

Shapes Prismatic shapes: solid or hollow.

Design Notes Metal extrusion is limited to ductile materials with melting points below 1700 C, commonly aluminum, copper, magnesium, low and medium carbon steels, low alloy steels, and stainless steels. The tolerance is often lower than expected because of creep and die wear; it can be improved by cold drawing as a secondary process. Symmetric crosssections, constant wall thickness, and generous radii are the easiest to form; the aspect ratio of the section should not exceed 14:1 for steel or 20:1 for magnesium. Impact extrusion is a cold process for metals (aluminum, copper, lead, magnesium, tin, zinc, carbon steels, low alloy steels) which combines the principles of forging and extrusion.

Polymer extrusion begins with powder or pellets; pressure is built up by a rotating screw, forcing the polymer through a heating chamber and through the die. Most polymers can be extruded (including those with particulate and short fiber-reinforcement). In ceramic extrusion a ceramic powder is mixed with a polymer binder and extruded like a polymer. The extruded section is then fired, burning off the binder and sintering the ceramic powder.

Technical Notes There are two variants of material extrusion: direct – where the die is stationary and the metal is forced through it; and indirect – where the die itself compresses the metal. Indirect extrusion has less friction between the billet and die, so the extrusion forces are lower but the equipment is more complex and the product length is restricted.

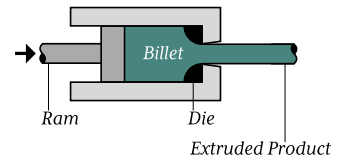
The Economics For metals, rolling is more economical for simple shapes and large product runs; for polymers, the tooling costs are relatively low although capital costs are high and secondary processing is often required.

Typical Products Tubing, window frame sections, building and automotive trim, aircraft structural parts, railings, rods, channels, plastic-coated wire, seals, filaments, film, sheet, pellets, bricks.

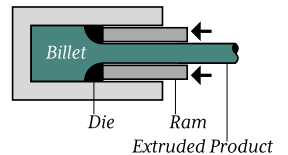
The Environment No special problems here.

Competing Processes For metals: rolling, drawing; for polymers: extrusion blow molding.

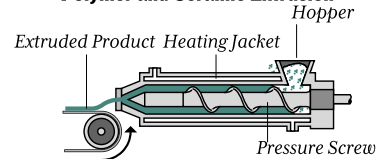
Direct Extrusion



Indirect Extrusion

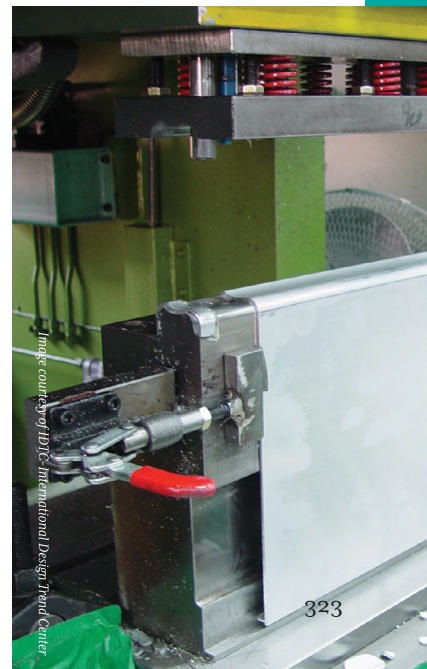


Polymer and Ceramic Extrusion

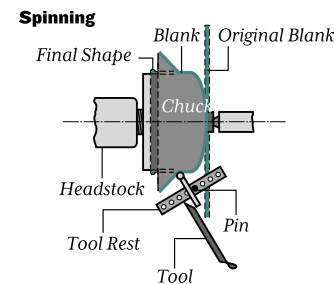
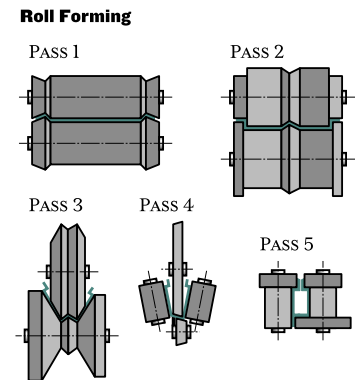
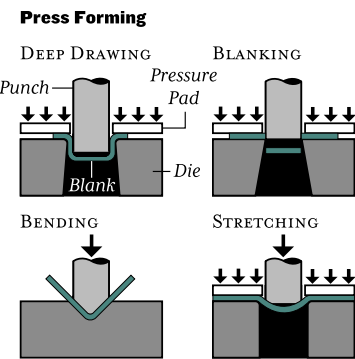


Attributes of Extrusion

Weight range, kg	1–100
Minimum thickness, mm	0.1–900
Shape complexity	Low
Allowable tolerance, mm	0.2–2
Surface roughness, μm	0.5–12.5
Economic batch size	1K–1000K



Press Forming, Roll Forming, and Spinning



Attributes of Press Forming, Roll Forming and Spinning

Weight range, kg	0.01-30
Minimum thickness, mm	0.2-5
Shape complexity	Med
Allowable tolerance, mm	0.1-0.8
Surface roughness, μm	0.5-12.5
Economic batch size	25K-250K

What Is It? Many products are made by cutting, pressing, punching, folding, or spinning of sheet. Press forming covers a range of sheet forming processes that use a die and a press; these include blanking, shearing, drawing, and stretching. They can be performed consecutively to form complex shapes. Tools are dedicated, so tooling costs are high. In roll forming a continuous strip of sheet metal is fed through a series of shaped rolls, gradually forming it to the desired profile. The process is suited for long lengths of constant, sometimes complex, cross-sections. Hollow components are possible by incorporating seam welding into the process. High production rates, tooling and capital costs make the process economic only for large production levels. In spinning a circular blank of sheet metal is formed over a rotating mandrel or forming block, against which it is pressed by a rigid tool or roller as it spins. The tools are very simple, made of wood or metal, and are therefore cheap.

Shapes Flat and curved thin-walled shapes. Rolling: prismatic shapes only. Spinning: curved thin-walled shapes.

Design Notes Skilled metal workers can form sheet into intricate shapes using drawing, bending, and forming operations. Shapes with holes, curves, recesses, cavities and raised sections are common. Sheet forming starts with sheet stock, giving the products an almost constant cross-section unless folded. Spinning is limited to relatively simple hemispherical, conical, or cylindrical shapes, although re-entrant shapes are possible.

Technical Notes Sheet forming is most commonly applied to metals, particularly steels, aluminum, copper, nickel, zinc, magnesium, and titanium. Polymer and composite sheet can be processed, though here the operations are limited to blanking and shearing.

The Economics The cost of sheet forming operations depends largely on tooling costs. Dedicated tools and dies are usually expensive, and require large batch sizes to make them economic. Processes with low-cost tooling, such as spinning, are best suited to small batch sizes, because they are labor intensive.

Typical Products Press forming: automobile body parts, casings, shells, containers. Stamping and blanking: smaller mechanical components such as washers, hinges, pans, and cups. Roll forming: architectural trim, window frames, roof and wall panels, fluorescent light fixtures, curtain rods, sliding door tracks, bicycle wheels. Spinning: rocket motor casings, missile nose cones, pressure vessels, kitchen utensils, light reflectors.

The Environment Sheet metal forming carries no particular environmental hazard.

Competing Processes Die-casting; injection molding.

Thermoforming

What Is It? Large thermoplastic sheet moldings are economically made by thermoforming. In vacuum thermoforming a thermoplastic sheet, heated to its softening point, is sucked against the contours of a mold, taking up its profile; it is then cooled, solidifying against the mold. Drape thermoforming relies partly on vacuum and partly on the natural sag of the hot polymer to form the shape. Plug-assisted thermoforming augments the vacuum with a compression plug. Pressure thermoforming uses a pressure of several atmospheres to force the hot polymer sheet onto the mold. Male or female molds are possible and – for vacuum thermoforming – can be machined from wood, polymer foam, or from aluminum (for larger batch sizes).

Shapes Curved thin-walled shapes.

Design Notes The low pressure in vacuum forming gives poor reproduction of fine details; pressure forming, using higher pressures, gives sharper features but is more expensive because wooden molds cannot be used. The surface of the sheet in contact with the mold tends to mark, so the tool is usually designed with the finished side away from the mold. Colored, textured, or pre-decorated sheet can be molded, reducing finishing costs.

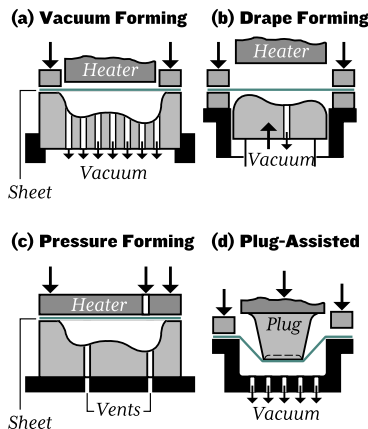
Technical Notes Thermoforming is used to shape thermoplastic sheet, particularly ABS, PA, PC, PS, PP, PVC, polysulphones, PBT, PET, foams, and short fiber-reinforced thermoplastics. The maximum depth-to-width ratio of the molding is in the range 0.5–2. Inserts can be molded in. The process is able to cope with a very large range of sizes from products as small as disposable drink cups to those as large as boat hulls; and it is economic for both small and large batch sizes. It gives products with excellent physical properties but the starting material is more expensive (sheet rather than pellet). The product has to be trimmed after forming, and sheet scrap cannot be directly recycled.

The Economics Both the capital and the tooling costs of thermoforming equipment are low but the process can be labor intensive.

Typical Products Appliances, refrigerated liners, bath tubs, shower stalls, aircraft interior panels, trays, signs, boat hulls, drink cups.

The Environment No environmental problems here.

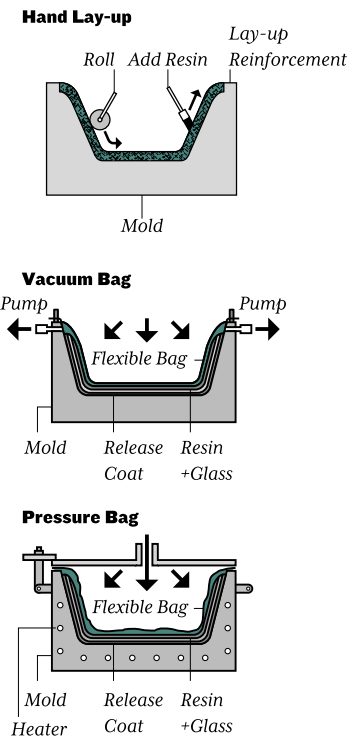
Competing Processes Injection molding (for large batch sizes); rotational molding.



Attributes of Thermoforming

Weight range, kg	0.003–50
Minimum thickness, mm	0.25–6
Shape complexity	Low
Allowable tolerance, mm	0.5–1
Surface roughness, μm	0.3–1.6
Economic batch size	10–100K

Lay-Up Methods



What Are They? The low density and high resilience of polymer-matrix composites gives them an increasingly large fraction of the market for shells, casings, body panels, and structural components. They can be formed in a number of ways.

In hand lay-up, an open mold (made of glass-reinforced polymers, wood, plaster, cement, or light metal alloys) is coated with a resin to give a smooth surface skin. When this has cured, a layer of reinforcement (woven or knitted glass or carbon fiber) is laid on by hand, resin is applied by a brush or spray gun, and the layer is rolled to distribute the resin fully through the fibers. The process is repeated, layer by layer until the desired thickness is reached. The type of weave influences its ability to take up double curvature (“drapability”): random mat (“glass wool”) and knitted fibers have good drapability; weaves with straight wefts do not. Flame retardants and inert fillers are added to reduce cost and improve properties. In spray-up a resin mixed with chopped fibers is sprayed into the mold; it is used for large components where the reinforcement fraction need not be large. In vacuum/pressure bag molding, the reinforcement and the resin are applied to the mold by conventional hand or spray-up methods. A bag is then placed over the curing composite and forced down onto it by vacuum or pressure, giving dense materials with better properties.

Shapes Curved thin-walled shapes with a single or double curvature.

Design Notes Lay-up methods give the greatest freedom to exploit the potential of fiber-reinforced polymers. They are generally limited to shapes with high surface area to thickness ratios. Ribs, bushes, and foam panels inserts are all possible. Vacuum and pressure bag methods give higher quality than hand lay-up because air bubbles in the resin are removed.

Technical Notes The resin systems are all thermosetting, based on polyesters, epoxies, vinyl esters, or phenolics. The reinforcement is commonly glass fiber but carbon and natural fibers, such as jute, hemp, or flax, can also be used.

The Economics The mold materials can be cheap (wood, cement); large moldings and small batch sizes are practical, but lay-up methods are labor intensive.

Typical Products Hand lay-up: boat hulls, building panels, vehicle bodies, ducts, tanks, sleighs, tubs, shower units. Vacuum/pressure bag molding: aerospace components, radomes.

The Environment Open molds lead to evaporation of resin, creating a health hazard: adequate ventilation is important.

Competing Processes Press molding; resin transfer molding.

Attributes of Lay-Up Methods

Weight range, kg	1-6000
Minimum thickness, mm	2-10
Shape complexity	Low/Med
Allowable tolerance, mm	0.6-1 mm
Surface roughness, μm	1-500
Economic batch size	1-500

Powder Methods

What Are They? When you make a snowman by squeezing and modeling snow, you are compacting and sintering a powder. Many materials are most easily formed by powder methods. The technique has particular value in shaping difficult materials – ceramics and refractory metals for instance – that are too brittle to deform and have high melting temperatures and so cannot be easily cast. In powder sintering, the loose powder is packed in a shaped mold of steel, graphite, or ceramic and sintered at a temperature, typically, of two-thirds of the melting temperature of the powder. In pressing and sintering, the powder is first compressed in a cold die, giving it sufficient strength to be handled, allowing it to be sintered as a free-standing body. Better densification, strength, and ductility are given by hot pressing, which combines compaction and sintering into one operation. Vacuum hot pressing is used for powders that are particularly sensitive to contamination by oxygen or nitrogen (titanium is an example). In hot isostatic pressing (HIPing), the powder is placed in a deformable metal container and then subjected to high temperature and high pressure (1100 C, 200 MPa) in an argon atmosphere that acts as the pressure medium. In powder extrusion or powder injection molding (also known as “metal injection molding”) the powder is mixed with up to 50% of a polymer binder and extruded or injection molded (See “Extrusion”). The resulting shape is sintered in a separate operation, burning off the polymer and bonding the powder particles.

Shapes Prismatic or simple three-dimensional shapes.

Design Notes Powder methods give great freedom of choice of materials (particularly as powders of different materials can be mixed to give composites) but they are limited in the shapes that can be made. Side walls must, in general, be parallel, undercuts at right angles to the pressing direction, and screw threads, lateral holes, and re-entrant grooves cannot be molded in easily. There is considerable shrinkage (up to 35%) on sintering – the dimensional changes must be allowed for.

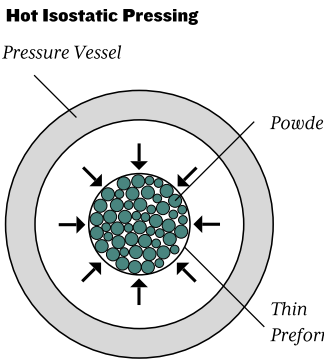
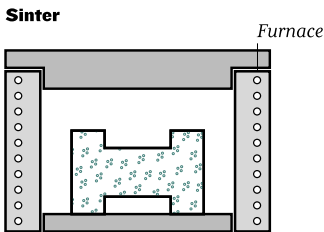
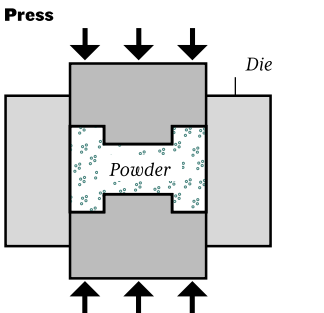
Technical Notes Powder methods are routinely used for brass, bronze, iron-based alloys, stainless steels, cobalt, molybdenum, titanium, tungsten, beryllium, metal matrix composites, and ceramics.

The Economics Powder methods are fast and use material efficiently, but powders are expensive.

Typical Products Powder sintering: filters, porous bearings, and low density ceramics. Pressing and sintering: small gears and cams, small bearings, electrical and magnetic components. Hot isostatic pressing: tool steel and tungsten carbide cutting tools, super alloy components for aerospace. Powder injection molding: spark plugs, heat engine components, medical and dental devices.

The Environment Burn-off of binder generates toxic fumes.

Competing Processes None that directly compete.

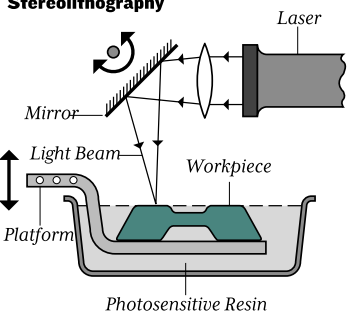


Attributes of Powder Methods

Weight range, kg	0.01–5
Minimum thickness, mm	1.5–8
Shape complexity	Low/Med
Allowable tolerance, mm	0.1–1
Surface roughness, μm	1.6–6.3
Economic batch size	1K–1000K

Laser Prototyping

Stereolithography



Attributes of Laser Prototyping

Weight range, kg	0.1–20
Minimum thickness, mm	0.5–100
Shape complexity	High
Allowable tolerance, mm	0.2–2
Surface roughness, μm	100–125
Economic batch size	1–100

What Are They? All designers dream of effortlessly transforming their visions into real three-dimensional objects, of arbitrary complexity, that can be handled, viewed, and tried out in the context in which they are to be used. Methods for rapid prototyping – one of the fastest-growing sectors of manufacturing technology – allow this. The input is a CAD file describing the form of the component; the output is a single realization of the component in polymer, metal, or compacted laminated paper. In stereolithography (SL) a photo-sensitive resin is polymerized by a UV laser beam that scans the surface of a bath containing liquid resin. Each scan creates a thin slice of the object; when one scan is complete the platform is lowered slightly (typically 0.1 mm) flooding the surface with fresh liquid that is polymerized by the next scan. The object is thus built layer by layer from the bottom up.

In selective laser sintering (SLS) the liquid resin is replaced by a fine heat-fusible powder (a thermoplastic or wax) that is melted by the scanning laser beam, creating a single slice of the object. The table is then lowered and a new layer of powder is spread across the surface by a wiper, ready for the next scan. The method has now been extended to sinter metals. In laminated object manufacture (LOM) the slices are created by laser cutting a sheet of paper coated with a thermoplastic. The paper is fed from a roller and the profile of one slice is cut by the laser; a heated roller then presses the slice onto the stack of previously cut slices, bonding it in place. The process is faster than the other two because the laser only traces the outline of the slice. It is best for large components with thick-wall sections. The finished material resembles wood.

Shapes Solid or hollow complex bulk shapes.

Design Notes Rapid prototyping in ABS or nylon offers the designer the ability to make prototypes of almost unlimited complexity. All the processes are slow: the time to make an object scales with volume for SL and SLS, and with surface area for LOM – imposing a practical size limit of about 300 mm.

Technical Notes Rapid prototyping systems are evolving very rapidly, and are already an essential part of the model-building capability of designers. Their speed and precision will increase and their cost will decrease in the future.

The Economics The cost of making an object depends on size and process – \$500–\$5000 gives an idea. This will decrease as faster systems become available.

Typical Products Rapid prototyping is widely used in product design to realize a three dimensional model of an evolving concept.

The Environment Liquid resins are volatile, fine powders can be explosive, and laser beams can damage eyes – all require appropriate precautions.

Competing Processes Deposition prototyping (next page).

Deposition Prototyping

What Are They? Think of the way in which the top of a wedding cake is built up: the icing is squeezed, like toothpaste, from a gun. Now reduce the scale by a factor of 100, and you have the basis of deposition-based rapid prototyping. The input – as with laser-based prototyping – is a CAD file describing in the form of the component; the output is a single realization of the component in polymer or wax. The figure shows one variant of the technology. In fused deposition modeling (FDM) a fine stream of thermoplastic or wax is deposited by a two-axis heated extrusion head. The semi-liquid polymer or wax is extruded from the heated head and deposited in layers, typically 0.1 mm thick, one layer at a time, starting at the base. Successive layers bond by thermal fusion. The process is well adapted to form ABS and nylon and requires no post-curing (making it faster). Overhangs can be created without support because the polymer sets very quickly. In ballistic particle manufacture (BPM) particles of molten thermoplastic are shot by a piezo-electric jet and freeze when they hit the object. The jet-head scans the surface, creating single layers at each scan, a range of thermoplastics and waxes can be used in the jet. In true three-dimensional printing the thermoplastic is jetted from a print head with up to 96 jets in a linear array, like an ink jet printer. The resolution is like that of the printer – about 300 dpi. The process, which is rapidly evolving, has the potential to build objects both accurately and quickly. All three processes can be adapted to deposit fine powders of metals or ceramics, though commercially available systems that do this are not yet available.

Shapes Solid or hollow complex bulk shapes.

Design Notes Rapid prototyping in ABS or nylon offers the designer the ability to make prototypes of strong materials and almost unlimited complexity.

Technical Notes Rapid prototyping systems are evolving very rapidly, and are already an essential part of the model-building capability of designers. Their speed and precision will increase and their cost will decrease in the future.

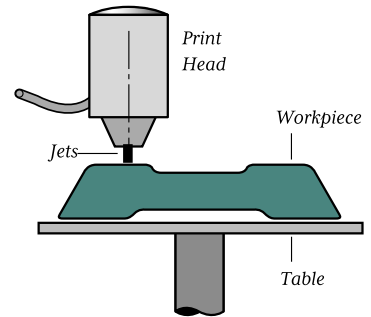
The Economics The cost of making an object depends on size and process – \$500–\$5000 gives an idea. This will decrease as faster systems become available.

Typical Products Rapid prototyping is widely used in product design to realize a three dimensional model of a evolving concept.

The Environment No particular hazards.

Competing Processes Laser-based prototyping.

Fused Deposition Modeling



Attributes of Deposition Prototyping

Weight range, kg	0.1–10
Minimum thickness, mm	1.2–100
Shape complexity	High
Allowable tolerance, mm	0.3–2
Surface roughness, μm	75–100
Economic batch size	1–100

Joining Profiles

The manufacture of a product involves many steps, one of which is that of assembly – and it is one that adds cost. Two techniques contribute to economical assembly: that of design to minimize the number of components and to enable ease of assembly, and that of selecting the joining process that best suits the materials, joint geometry, and the required performance of the joint during its life. The figure on the first text page shows joint geometries with their common names.

In this section we have assembled information for representative joining processes listed on the facing page. Three broad families can be distinguished: adhesives, mechanical fasteners, welding. The pages that follow give information about these. The choice of process also depends on the materials to be joined and the geometry of the joint. The processes used to weld polymers differ in obvious ways from those used to weld metals; less obviously, adhesives and mechanical fastening, too, are material-specific. Many processes can join only components made of the same material: steel to steel, polyethylene to polyethylene. Others can bond dissimilar materials: metal to glass, or polymer to ceramic, or composite to metal.

More information can be found in the sources listed under “Further Reading.”

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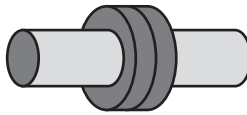
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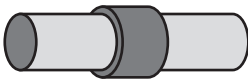
Cylinder to cylinder (butt)



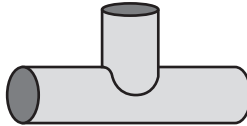
Cylinder to cylinder (flange)



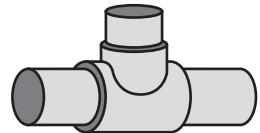
Cylinder to cylinder (scarf)



Cylinder to cylinder (sleeve)



Cylinder (plain intersect)



Cylinder (sleeved intersect)

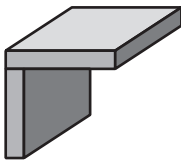


Plate to plate (corner)

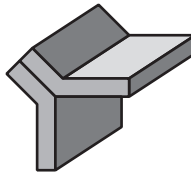


Plate to plate (edge)

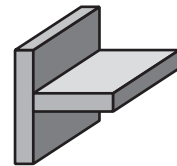


Plate to plate (tee)

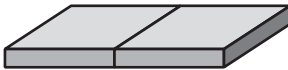


Plate to plate (butt)



Plate to plate (scarf)



Plate to plate (tongue and groove)

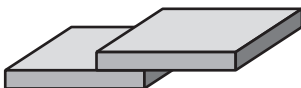


Plate to plate (single lap)

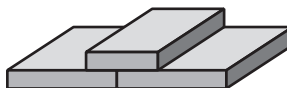


Plate to plate (strapped lap)

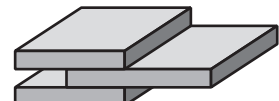


Plate to plate (double lap)



Plate to plate (landed lap)

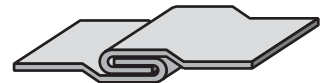
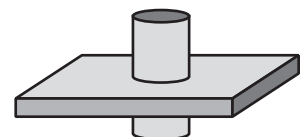
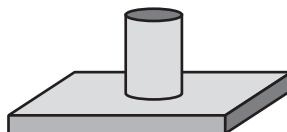


Plate to plate (locked lap)



Joint Geometries

The choice of process depends on geometry; modifying the geometry (replacing butt by lap, for instance) can sometimes allow a cheaper process.

Further Reading

Bralla, J.G. (1998) "Handbook of Product Design for Manufacture," 2nd edition, McGraw-Hill, New York, NY, USA. ISBN 0-07-007139-x. (The Bible – a massive compilation of information about manufacturing processes, authored by experts from different fields, and compiled by Bralla. A handbook rather than a teaching text.)

DeGarmo, E.P., Black, J.T. and Kohser, R.A. (1984) "Materials and Processes in Manufacturing," Macmillan Publishing Company, New York, NY, USA. ISBN 0-471-29769-0. (A comprehensive text focusing on manufacturing processes, with a brief introduction to materials. The perspective is that of metal processing; the processing of polymers, ceramics, and glasses gets much briefer treatment.)

Houldcroft, P. (1990) "Which Process?," Abington Publishing, Cambridge, UK. ISBN 1085573-008-1. (Brief profiles of 28 welding and other processes for joining metals, largely based on the expertise of TWI International in the UK. Good, but like Wise (below), difficult to get.)

Hussey, R. and Wilson, J. (1996) "Structural Adhesives: Directory and Data Book," Chapman & Hall, London. (A comprehensive compilation of data for structural adhesives from many different suppliers.)

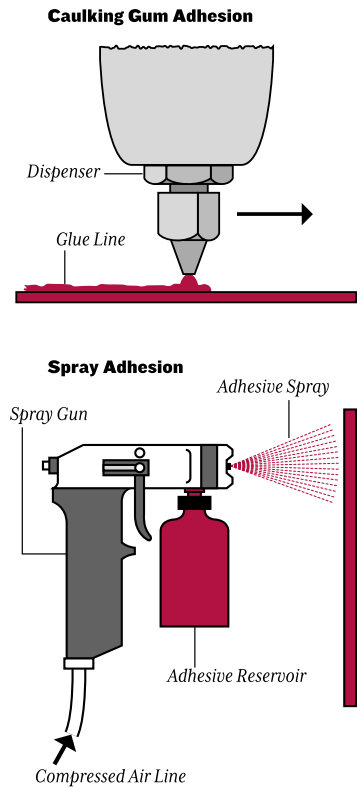
Kalpajian, S. (1984) "Manufacturing Processes for Engineering Materials," Addison-Wesley, Reading, MA, USA. ISBN 0-201-11690-1. (A comprehensive and widely used text on manufacturing processes for all classes of materials.)

Le Bacq, C., Jeggy, T. and Brechet, Y. (1999). "Logiciel d'aide a la pre-selection des procedes d'assemblage," INPG/CETIM, St Etienne, France.

Lesko, J. (1999) "Materials and Manufacturing Guide: Industrial Design," John Wiley & Sons, New York, NY, USA. ISBN 0-471-29769-0. (Brief descriptions, drawings, and photographs of materials and manufacturing processes, with useful matrices of characteristics, written by a consultant with many years of experience of industrial design.)

Swift, K. and Booker, J.D. (1998) "Process Selection: From Design to Manufacture," John Wiley & Sons, UK. ISBN 0-340-69249-9. (Datasheets in standard formats, for 48 processes, 10 of which are for joining.)

Wise, R.J. (1999) "Thermal Welding of Polymers," Abington Publishing, Cambridge, UK. (A compilation of information on processes for welding polymers, largely based on the expertise of TWI International in the UK. Good, but difficult to get.)



Adhesives

Attributes of Adhesives

Size of joint	Unrestricted
Maximum thickness, mm	Unrestricted
Unequal thickness?	Yes
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	16–180

Adhesives

What Are They? Adhesives – glues – are so ancient a technology that they have become part of the language: “...to cement a friendship,” “...the bonds of family,” “...adhering to policy.” And ancient the technology is: all early civilizations seem to have known how to make starch paste and glues from animal gelatines, and how to join materials with bitumen and gum arabic. Synthetic adhesives appeared around 1900, and since then advances in polymer chemistry have greatly expanded their range and performance. Synthetic structural adhesives are now used in every industrial sector. Structural adhesives are those that are used to perform some mechanical function, though they may have a secondary role as a sealant. Many are rigid, giving a stiff bond, but flexible adhesives also play an important role in design. Within each group, it is usual to use a classification based on chemistry.

Joint Type All geometries, particularly lap joints.

Design Notes Adhesives have a number of features that allow great design freedom: almost any material or combination of materials can be adhesively bonded; they can be of very different thickness (thin foils can be bonded to massive sections); the processing temperatures are low, seldom exceeding 180°C; the flexibility of some adhesives tolerates differential thermal expansion on either side of the joint; adhesive joints are usually lighter than the equivalent mechanical fasteners; and adhesives can give joints that are impermeable to water and air. The main disadvantages are the limited service temperatures (most adhesives are unstable above 190 C, though some are usable up to 260 C), the uncertain long-term stability, and the unpleasant solvents that some contain.

Technical Notes Adhesive joints resist shear, tension, and compression better than tear or peel – these last two should be avoided. Typical lap shear strengths are in the range 8–45 MPa. For joints loaded in shear, width “normal to the direction of shear” is more important than length “parallel to the shear direction.” Butt joints are practical only when the area is large. Thin bond lines (typically 25 microns) are best, except when high impact strength is required. The essential equipment for adhesive bonding includes hot glue-guns and caulking-guns, both of which are used to apply adhesives in a paste or semi-liquid form. Spray guns are used to apply liquid adhesives and can be automated. Brushes and sprays are used for manual application.

The Environment Good ventilation is essential wherever adhesives are used.

Competing Processes Mechanical fasteners – although these generally require holes with associated stress concentrations.

Acrylic Adhesives

Acrylic adhesives are two-part systems which, when mixed or activated by UV radiation, cure to form a strong, impact resistant bonding layer. Mostly used for wood-to-metal bonds.

Features: durable, tough, water resistant, optically clear, able to bond a wide range of materials.

Typical Products: aerospace, automotive, computer components.

Adhesives, Continued**Cyanoacrylate Adhesives**

Cyanoacrylate adhesives are familiar as “super glue.” They are single-part systems that cure in seconds when exposed to damp air to give a strong, rather brittle bond.

Features: cyanoacrylate adhesives bond to practically anything, and do so “instantly” requiring no heat or clamping.

Typical Products: rapid joining of small parts, general domestic repairs.

Epoxies and Epoxy-Phenolics

Epoxies and epoxy-phenolics are thermosetting adhesives with high tensile strengths (up to 45 MPa) and low peel strengths (1.8 kg/mm), resistant to solvents, acids, bases, and salts. Nylon-epoxies have the highest strengths and are used primarily to bond aluminum, magnesium, and steel. Epoxy-phenolics retain their strength up to 150–250 C and are used to bond metals, glass, and phenolic resins. Most are two-part systems, curing at temperatures between 20 and 175 C, depending on grade. They are used in relatively small quantities because of price: but, together with imide-based adhesives, they dominate the high performance adhesives markets.

Features: good adhesion to a wide range of substrates, with low shrinkage and good mechanical properties from –250 to 260 C.

Matrix for Adhesives

Bonding of different materials.

Typical Products: widely used in the aerospace, automotive, and boat building industries.

Metals	Acrylic, CA, Epoxy, PU, Phenolic, Silicone		<div>Key</div> <div>Polyurethane = PU</div> <div>Thermoplastic = Hot-melt</div> <div>Cyanoacrylate = CA</div> <div>Polyester = PES</div> <div>Polyvinylacetate = PVA</div> <div>Ceramic-based = Ceram</div>						
	Wood	Acrylic, Epoxy, Phenolic, Hot-melt						Epoxy, Phenolic, PVA	
Polymers	Acrylic, CA, Epoxy, Phenolic	Epoxy, PU, Phenolic, PVA						Acrylic, CA, Epoxy, Phenolic	
Elastomers	CA, Epoxy, Silicone	Acrylic, Phenolic, Silicone						CA, Epoxy, Phenolic, Silicone	PU, Silicone
Ceramics	Acrylic, CA, Epoxy, Ceram	CA, Epoxy, PVA, Ceram						Acrylic, Epoxy, PU, PVA, Ceram	Acrylic, Epoxy, PU, PVA, Silicone
Fiber Composites	Acrylic, CA, Epoxy, Imide	Acrylic, CA, Epoxy, PVA	Acrylic, Epoxy, PVA, Silicone	Epoxy, PU, Silicone	CA, Epoxy, Silicone	Epoxy, Imide, PES, Phenolic			
Textiles	PU, Hot-melt	Acrylic, PVA, Hot-melt	Acrylic, PVA	Acrylic, PU, PVA	Acrylic, PU, PVA, Hot-melt	Acrylic, PU, PVA	PVA, Hot-melt		
Metals	Wood	Polymers	Elastomers	Ceramics	Fiber Composites	Textiles			

Key

Polyurethane = PU
 Thermoplastic = Hot-melt
 Cyanoacrylate = CA
 Polyester = PES
 Polyvinylacetate = PVA
 Ceramic-based = Ceram

Adhesives, continued**Imide-based Adhesives (Dismaleimides, BMI and Polyimides, PI)**

Imide-based adhesives, like epoxies, are widely used as a matrix in fiber-reinforced polymers. They have better elevated temperature performance than most other organic adhesives. They are used to bond ceramics and metals.

Features: excellent dielectric properties (hence their use in radomes); BMIs can be used at temperatures as extreme as -250°C and 230°C ; PIs up to 300°C .

Typical Products: radomes.

Phenolic Adhesives

Phenolic adhesives are as old as Bakelite (1905), which they resemble chemically. Phenolics are sometimes blended with epoxies and neoprenes.

Features: high strength, good water resistance and heat resistance, flame retardant.

Typical Products: manufacture of plywood, chipboard, and laminated wood structures; abrasive wheels and brake pads; foundry use for sand binding.

Polyurethanes

Polyurethanes include both polyurethane- and isocyanate-based adhesives, with lap shear strengths of about 8 MPa.

Features: bond well to a wide range of materials, are tough and flexible, have good resistance to water and solvents, and perform well from -250 to 80°C .

Typical Products: widely used in the automotive, construction, furniture, and footwear industries.

Silicones (SIL)

Silicones are synthetic polymers in which silicon replaces carbon as the major chain element. Most are two-part systems. Their chemistry gives them exceptional flexibility and chemical stability.

Features: flexible, useful properties from -115 to 260°C ; good resistance to water and UV and IR radiation.

Typical Products: adhesives and seals in automotive, construction, and marine industries.

Adhesives, continued**Hot-melt Adhesives**

Hot-melt adhesives are based on thermoplastics such as PE, nylons (PA), EVA, and polyesters. These melt on heating to 100–150 C. By modifying their chemistry, they can be made to stick to other materials. Used to bond woods, textiles, polymers, elastomers, and metals.

Features: fast and easy to use; no solvent fumes; a wide range of chemistries that can be adapted to specific tasks.

Typical Products: prototyping, crafts.

Anaerobic Adhesives

Anaerobic adhesives cure at room temperature when deprived of oxygen.

Features: strong bond with low shrinkage.

Typical Products: thread-locking of mechanical fasteners; fixing of gears and bearings, large flat panels.

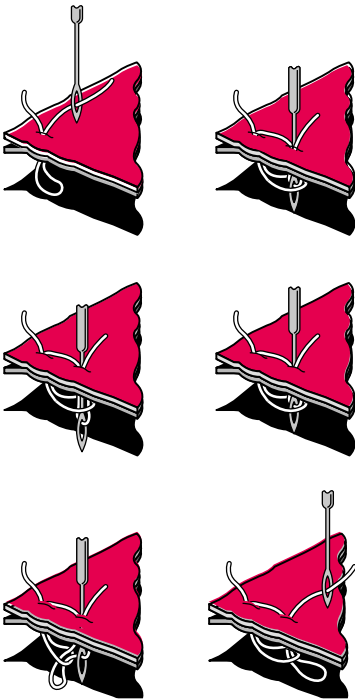
Ceramic-based Cements

Ceramic-based cements are inorganic two-part systems that set to give a bond that is stable to high temperatures; used to bond thermal insulation to ceramics, metals, glass, or wood.

Features: chemically stable bond, usable up to 1600 C.

Typical Products: bonding of refractory bricks in kilns and furnaces; foundry applications.

Sewing



What Is It? Sewing, like investment casting and enameling, has been practiced for at least 5000 years – indeed, there is evidence that it is much older still. In sewing, a series of stitches are applied, using one or more continuous threads of fibers, to join two or more thicknesses of material. There are many types of stitching, broadly described as “lock stitch” in which loops of one thread pass through the material and are locked on the other side by a second thread; or “chain stitch” in which a single thread zigzags through the material. Sewing machines automate the process. The figure shows a chain stitch of a single lap joint.

Joint Type Lap and butt.

Design Notes Sewing is an exceptionally flexible process, both in the range of materials it can join and in the shapes to which it can be applied. It provides not only mechanical fastening, but also decoration, often of a very elaborate kind.

Technical Notes Dissimilar materials can be joined. The threads used for conventional sewing are the natural fibers cotton, silk, and flax, the cellulose derivative (rayon or viscose), and drawn polymer fibers made from polyethylene, polyester, polyamide (nylons), or aramids (such as Kevlar). It is also possible to sew with metal threads. The joining thread or fiber must be sufficiently strong and flexible to tolerate the tensions and curvatures involved in making a stitch. All fabrics, paper, cardboard, leather, and polymer films can be sewn. Sewing can also be used to join fabric and film to metal, glass, or composite if eye-holes for the threads are molded or cut into these. There are many possible joint configurations, some involving simple through-stitching of a single lap or zigzag stitching across a simple butt, others requiring folding to give locked-lap and butt configurations.

The Economics Hand or small electric sewing machines are inexpensive; large automated machines can be expensive. Sewing is fast, cheap, and very flexible, both in the materials it can join, and in the joint configurations.

Attributes of Sewing

Size of joint	Unrestricted
Maximum thickness, mm	1–10
Unequal thickness?	Limited
Join dissimilar materials?	Yes
Impermeable?	No
Processing temp., °C	16–30

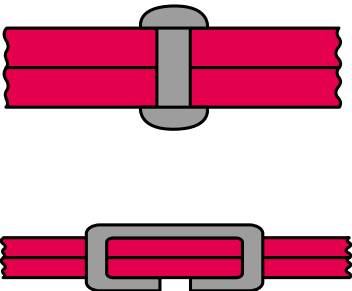
Typical Products Sewing is the principal joining process used by the clothing industry. It is important in tent and sail making, shoe construction, and book binding. It is used to join polymer sheet to make wallets, pockets, cases, and travel gear.

The Environment The thimble was devised to protect the finger from puncture when sewing. This minor risk aside, sewing offers no threat to health or safety, and is environmentally benign.

Competing Processes Adhesives; threaded fasteners.

Rivets and Staples

What Are They? Mechanical fasteners have three special attractions: they do not require heat; they can join dissimilar materials; and these can be of very different thickness. Rivets are widely used in aircraft design – a testament to their strength, permanence, and reliability. Riveting is done by inserting a stud with a head on one end through pre-drilled holes in the mating components, and clinching (squashing) the other end where it sticks out by hitting it with a shaped hammer. Staples – familiar as a way of binding paper and attaching leather and cloth to frames in furniture – are fast and cheap; they can also be used to assemble sheet metal. Staples are applied with a spring-loaded, electric or pneumatic jig that forces the staple through the materials and onto a grooved anvil, bending the legs inwards and pinching the materials together. In blind stapling there is no anvil – the legs of the staple are simply driven through one material into the other, where they stick in the same way that nails do.



Joint Type Lap.

Design Notes Both rivets and staples can be used to join similar materials, but they can also be used to join one material to another even when there is a large difference in their strengths – leather or polymer to steel or aluminum for instance. Both allow great flexibility of design although a stress concentration where the fastener penetrates the material should be allowed for. Rivets should have heads that are 2.5–3 times the shank diameter; when one material is soft, it is best to put a washer under the head on that side to avoid pull-out. Staples are good when materials are thin; when metal is stapled, the maximum thickness is about 1 mm, when non-metallic it can be up to 10 mm.

Technical Notes Rivets and staples are usually metallic: steel, aluminum, and copper are common. Polymeric rivets and staples are possible: they are clinched by using heat as well as pressure. Almost any material, in the form of sheet, mesh, or weave, can be joined by these methods; stapling also allows wire to be joined to sheet.

The Economics Both riveting and stapling are cheap, fast, and economic even for very low production runs. Equipment, tooling, and labor costs are all low. The processes can be automated.

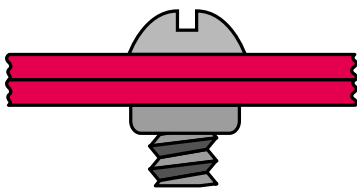
Typical Products Stapling: joining of paper, leather, cloth, fiberboard. Rivets are extensively used in aerospace, automotive, and marine applications, but have much wider potential: think of the riveting of the leather label to the denim of jeans.

The Environment The sound of the shipyard is that of riveting – it can be very loud. Overenthusiastic staplers have been known to staple themselves. These aside, both processes are environmentally benign.

Competing Processes Adhesives; sewing; threaded fasteners.

Attributes of Rivets and Staples	
Size of joint	Unrestricted
Maximum thickness, mm	0.01–10
Unequal thickness?	Limited
Join dissimilar materials?	Yes
Impermeable?	With sealant
Processing temp., C	16–30

Threaded Fasteners



Attributes of Threaded Fasteners

Size of joint	Unrestricted
Maximum thickness, mm	Unrestricted
Unequal thickness?	Yes
Join dissimilar materials?	Yes
Impermeable?	With sealant
Processing temp., C	16–30

What Are They? When we get “down to the nuts and bolts” we are getting down to basics. Screws are as old as engineering – the olive press of Roman times relied on a gigantic wooden screw. Threaded fasteners are the most versatile of mechanical fasteners, with all the advantages they offer: they do not involve heat, they can join dissimilar materials of very different thickness, and they can be disassembled. Ordinary screws require a pre-threaded hole or a nut; self-tapping screws cut their own thread.

Joint Type Most commonly, lap; but almost all joints can be adapted for threaded attachment.

Design Notes Mechanical fasteners allow great freedom of design, while allowing replacement of components or access because of the ease of which they can be disassembled.

They can be used up to high temperatures (700 C) and – with proper location – allow high precision assembly.

Technical Notes Threaded fasteners are commonly made of carbon steel, stainless steel, nylon, or other rigid polymers. Stainless steel and nickel alloy screws can be used at high temperatures and in corrosive environments. Tightening is critical: too little, and the fastener will loosen; too much, and both the fastener and the components it fastens may be damaged – torque wrenches overcome the problem. Locking washers or adhesives are used to prevent loosening.

The Economics Threaded fasteners are cheap, as is the equipment to insert them when this is done by hand. But the insertion is difficult to automate, making other methods (welding, riveting, adhesives) more attractive for a permanent bond.

Typical Products Threaded fasteners are universal in engineering design. But increasingly their use is becoming limited to products in which disassembly or the ability to have access is essential because other joining methods are cheaper, less likely to loosen, lighter and easier to automate.

The Environment Threaded fasteners have impeccable environmental credentials.

Competing Processes Snap fits, rivets and staples, adhesives, sewing.

Snap Fits

What Are They? Snap fits, like other mechanical fastenings, involve no heat, they join dissimilar materials, they are fast and cheap and – if designed to do so – they can be disassembled. It is essential that the snap can tolerate the relatively large elastic deflection required for assembly or disassembly. Polymers, particularly, meet this requirement, though springy metals, too, make good snap fits.

Joint Type All geometries can be adapted for snap fitting, provided the material is chosen appropriately.

Design Notes Snap fits allow components of every different shape, material, color, and texture to be locked together, or to be attached while allowing rotation in one or more direction (snap hinges). The snap fit can be permanent or allow disassembly, depending on the detailed shape of the mating components. The process allows great flexibility in design and aesthetic variety.

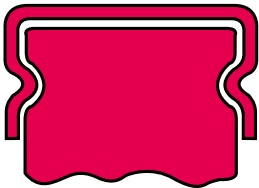
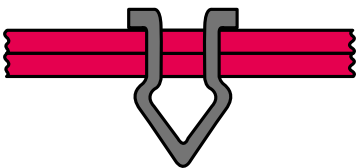
Technical Notes The best choices are materials with large yield strains (yield strain = yield strength/elastic modulus) and with moduli that are high enough to ensure good registration and positive locking. Polymers (particularly SAN, nylons, polyethylenes, and polypropylenes) have much larger values of yield strain than metals. Elastomers have the largest of all materials, but their low modulus means that the assembly will be too flexible and pop apart easily. Among metals, those used to make springs (spring steel, copper beryllium alloys, and cold worked brass) are the best choices, for the same reasons.

The Economics Snap fits are fast and cheap, and they reduce assembly time and cost, both in production and in use. Hand assembly requires no special equipment. Automated assembly requires equipment that can be expensive, but it is very fast.

Typical Products Snap fits are increasingly used because of the freedom of material and shape that they allow. Typically they are used to join small or medium sized polymer parts, metal casings, sheet parts etc.

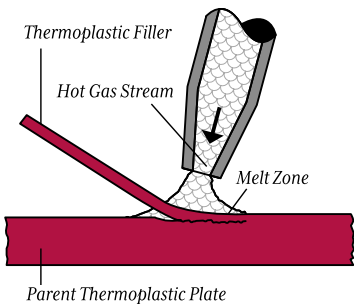
The Environment Snap fits disassemble easily, making recycling easier. In this and every other way they are environmentally benign.

Competing Processes Adhesives; staples; sewing; threaded fasteners.



Attributes of Snap Fits

Size of joint	Restricted
Maximum thickness, mm	Unrestricted
Unequal thickness?	Yes
Join dissimilar materials?	Yes
Impermeable?	Possible
Processing temp., C	16–30



Attributes of Hot Gas Welding

Size of joint	Unrestricted
Maximum thickness, mm	2.5–10
Unequal thickness?	Limited
Join dissimilar materials?	If similar T_m
Impermeable?	Yes
Processing temp., C	200–300

Hot Gas Welding

What Is It? Hot gas welding is a way of joining thermoplastics that is similar, in many ways, to the gas welding of metals. The weld torch is just a souped-up hairdryer that directs a stream of hot gas at scald-searing temperatures (200–300 C) at the joint area and at a rod of the same thermoplastic as the substrate. Polymers are very viscous when heated, so they do not flow in the way that metals do – that is why filler material is needed; the filler is pressed into the softened joint to form the bond. The process is slow and poorly adapted for mass production, but it is easily portable, making it the best way to assemble and repair large polymer components.

Joint Type All geometries, particularly plate to butt and lap.

Design Notes Hot gas welding is limited to thermoplastics. It is a manual process, best suited to on-site assembly of large structures – pipes, liners, and roof membranes for example. It cannot be used with very thin materials – 2.5 mm is the minimum.

Technical Notes Hot gas welding is commonly used to join polyethylene, PVC, polypropylene, acrylic, some blends of ABS, and other thermoplastics. The welding tool contains an electric heater to heat the gas, air, nitrogen, or CO₂ and a nozzle to direct it onto the work piece. If air is used, it is provided by a compressor or blower; nitrogen or CO₂ require a more complicated supply of gas.

The Economics The equipment cost and set-up time are both low, making this an economic process that can be performed on site; but it is slow and not suitable for mass production.

Typical Products Installation and repair of thermoplastic pipe and duct work, the manufacture of large chemical-resistant linings, the assembly of storage bins, and architecture uses for joining polymer roofing like that of the Millennium Dome in London.

The Environment No problems here – just a little hot air.

Competing Processes Laser welding; threaded fasteners; adhesives.

Hot Bar Welding

What Is It? The simplest of all welding processes for polymers is the one that you can use in your kitchen to seal food into freezer-bags: hot bar welding. In this process, overlapping thermoplastic polymer films are pinched between electrically heated, PTFE coated, bars. One bar is hinged to allow the films to be inserted and removed. Mechanical or pneumatic actuators close the bar and exert the pinch force. The joint itself is heated by conduction through the film, limiting the film thickness to less than 0.5 mm. A typical weld in a 100 micron thermoplastic film takes 1–3 seconds. Impulse welding is a modification of hot bar welding in which the bars are pulse-heated, giving an additional control of quality.

Joint Type Lap.

Design Notes The process is limited to thermoplastics and to lap joints between sheets, both of them thin. But it is fast, cheap, and clean, lending itself to the sealing of food, packaging, drugs, and medical equipment. The shape of the weld is defined by the shape of the bar, which can have a complex surface profile.

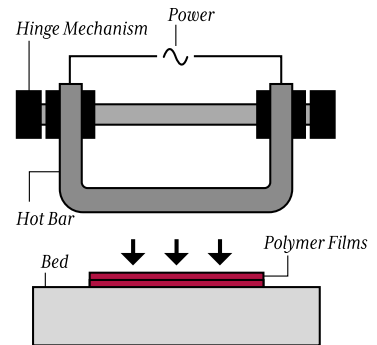
Technical Notes Control of time, temperature, and pinch-pressure are essential for a good joint – impulse welding is one way of controlling the first two of these. The time, t , to form a bond varies inversely with the thermal diffusivity, a , of the polymer, and is proportional to the square of the thickness, x , of the sheet ($t = x^2/2a$), so adjustments are needed when material or thickness are changed.

The Economics The process is cheap, fast, and uses low-cost equipment and tooling.

Typical Products Hot bar and impulse welding are widely used for sealing of polymer packaging for the food industry, for shrink-wrapped packs, for medical and general packaging. They are used to bond polymer films to polymer moldings, to make transparent file pockets, and may other similar applications.

The Environment The process is clean, involves no chemicals, generates no fumes, and consumes little energy; it is – in a word – eco-benign.

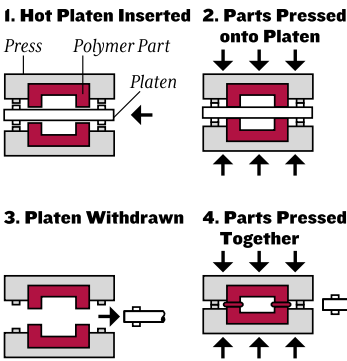
Competing Processes Laser welding; adhesives; sewing.



Attributes of Hot Bar Welding

Size of joint	Restricted
Maximum thickness, mm	0.05–0.5
Unequal thickness?	Limited
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	180–280

Hot Plate Welding



Attributes of Hot Plate Welding

Size of joint	Restricted
Maximum thickness, mm	1–30
Unequal thickness?	Limited
Join dissimilar materials?	No
Impermeable?	Yes
Processing temp., C	190–290

What Is It? Hot plate welding makes butt joints between bulk thermoplastic components, in a kind of inversion of the way that hot bar welding makes lap joints. The components to be joined are held in fixtures that press them against an electrically heated, PTFE coated, platen, melting the surface and softening the material beneath it. The pressure is lifted, the tool withdrawn, and the hot polymer surfaces are pressed together and held there until they have cooled. Hot plate welding can be used to form joints of large area – for example, the joining of large polyethylene gas and water pipes. The process is relatively slow, requiring weld times between 10 seconds for small components and 1 hour for very large.

Joint Type Plate to plate (butt).

Design Notes Hot plate welding can join almost all thermoplastics except nylons, where problems of oxidation lead to poor weld quality. The joint strength is usually equal to that of the parent material but joint design is limited to butt configurations. If the joint has a curved or angled profile, shaped heating tools can be used.

Technical Notes Precise temperature control of the hot plate is important for good joints. The plate temperature is generally between 190 and 290 C depending on the polymer that is to be joined. Pressure is applied hydraulically or pneumatically. Most thermoplastic components can be welded by the hot plate method, but it is most effective for joining large components made from polyethylene, polypropylene, or highly plasticized PVC. It creates a strong bond, impermeable to gas or water.

The Economics Equipment and tooling are moderately cheap, but the process can be slow.

Typical Products The process is used to make automotive hydraulic reservoirs and battery cases; to join unplasticized PVC door and window frames; to join thermoplastic pipes for gas and water distribution; and for sewers and outflows up to 150 mm in diameter. It is also used for smaller things: tail-light assemblies, water-pumps, refrigerator doors.

The Environment The process is clean and involves no unpleasant chemicals, and is generally eco-friendly.

Competing Processes Hot gas welding; friction welding.

Ultrasonic Welding

What Is It? If you want to weld using ultrasound, you need an ultrasonic generator, a converter (transducer), a booster, and a welding tool, bizarrely called a sonotrode. The generator for ultrasonic welding converts 50 Hz mains voltage into a 20 kHz signal. The converter uses the reverse piezo-electric effect to transform this into mechanical oscillations. The booster and the sonotrode transmit this to the weld zone in such a way as to create an oscillating displacement of 10–30 microns. A static pressure of 2–15 MPa is applied across the surfaces to be joined and the power switched on to make them slide, heat, roughen, and bond.

Joint Type Plate to plate (butt and lap).

Design Notes Ultrasonic welding produces fast, strong, clean, and reliable welds in both polymers and metals. For polymers, the process is principally used for thermoplastic film and sheet. It can join dissimilar materials of differing thickness, applying either spot or seam welds. Most metals can also be ultrasonically welded. There is some increase in temperature at the sliding surface, but it is well below the melting temperature of the material. Instead, it appears that the rapid reversal of stress breaks up surface films and contaminants, and local plasticity, coupled with some diffusion, creates the bond. The process offers short process times (e.g. 3 seconds per weld) and relatively low temperatures, minimizing damage to the material adjacent to the weld.

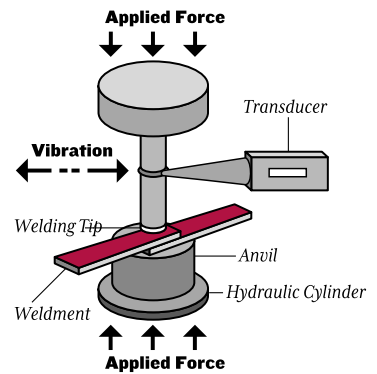
Technical Notes Ultrasonic welding is generally limited to the joining of thin materials – sheet, film, or wire – or the attachment of thin sheet to heavier structural members. The maximum thickness, for metals, is about 1 mm. The process is particularly useful for joining dissimilar metals. Because the temperatures are low and no arcing or current flow is involved, the process can be applied to sensitive electronic components. Joint shear strengths up to 20 MPa are possible.

The Economics Ultrasonic welding is fast and clean. Up to 1000 pieces an hour can be joined.

Typical Products Polymers: the process is widely used in the automotive, appliance, medical, textile, and toy industry. Typical assemblies include sealed tail-light assemblies with clear lenses and opaque bodies, double-layer insulated drinking cups, decorative multi-color name plate panels and toys. Metals: spot or line welding of thin sheet, joining of dissimilar metal in bi-metallics, micro-circuit electrical contacts, encapsulating explosives or chemicals.

The Environment The process has enviable environmental credentials. It is totally clean – no fumes, no chemicals, no electrical, or other hazards. The input energy is almost entirely transmitted to the joint, giving energy efficiency far exceeding that of thermal processes.

Competing Processes Threaded fasteners, laser welding.



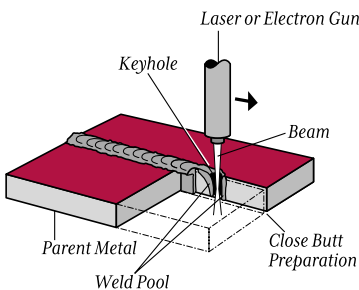
Attributes of Ultrasonic Welding

Size of joint	Restricted
Maximum thickness, mm	
(metals)	0.01–1
(polymers)	0.1–3
Unequal thickness?	Limited
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., °C	
(metals)	300–600
(polymers)	100–250



Power-beam Welding

Power-beam Welding: Metals



Attributes of Power-beam Welding: Metals

Size of joint	Restricted
Maximum thickness, mm	
(e-beam)	1-200
(laser beam)	0.2-20
Unequal thickness?	Limited
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	600-2k

What Is It? Electron and laser beams are the stuff of death-rays – invisible, deadly accurate, and clean – no smoke, no fumes, no mess. Both are used to weld metals; lasers can weld polymers too. In electron-beam welding, melting is produced by the heat of a focused beam of high velocity electrons. The kinetic energy of the electrons is converted into heat when it hits the work piece, which has to be contained in a vacuum chamber, and it must be a conductor. No filler metal is used. The process is more energy-efficient than laser-beam welding, allowing higher power densities and the ability to weld thicker plates. In laser-beam welding, the heat source is a narrow beam of coherent monochromatic light. The process is more precise than e-beam welding and takes place in air, allowing greater design freedom, but the penetration depth is less (maximum 20 mm in metals). Shielding gas is blown though a surrounding nozzle to protect the weld. Again, no filler metal is used.

It is possible to laser weld thin, semi-transparent, or opaque polymer films by simply scanning the beam across them, melting them right through, but this is not the best way to use lasers. The trick in welding polymers is to arrange that the beam is absorbed where it is most useful – at the joint interface. For transparent polymers this can be achieved by spraying a thin film of IR- or UV-absorbing dye, invisible to the human eye, onto the surface where the weld is wanted; the laser beam passes through the transparent upper sheet (which can be thick – up to 10 mm) without much energy loss. But when it hits the dye at the interface it is strongly absorbed, melting the polymer there and creating a weld while leaving most of the rest of the material cold. Scanning the beam or tracking the work piece gives a line weld up to 10 mm wide.

Joint Type Metals: All joint geometries are possible. Polymers: lap joints.

Design Notes The high power density in the focused beam gives narrow welds in metals with minimal penetration of heat into the work piece, allowing high weld speeds with low distortion. Accurate machining of mating components is needed, since no filler metal is used. The processes allow products to be made that could not be fabricated in any other way.

Welding polymers (particularly transparent polymers) without an interfacial dye is limited to the joining of thin thermoplastic film and sheet. Welding with a dye gives more control and allows thicker sections. Dissimilar materials can be joined, although their melting temperatures must be comparable. The main feature of the process is that it is non-contact, and exceptionally clean and fast.

Technical Notes Electron beams have a power of 1-100 kw, allowing welding of metal plate from 1 to 200 mm thick, but the process requires a vacuum chamber, limiting the size of the assembly. Laser-beam equipment has lower beam power – typically 500 w-5 kw, although lasers up to 25 kw exist. Laser-beam welding is preferred in the microelectronics industry because it is clean and requires no vacuum chamber. Electron-beam welding – because of the vacuum – is particularly suited for refractory metals such as tantalum, niobium, molybdenum, and tungsten. Laser welding can be used for these too, but it is essential that the metal should not have a shiny surface since this reflects the beam. Coatings are available to increase absorption. The strength of a well-designed laser-welded lap joint in polymers often exceeds that of the parent film or plate. For thin films the weld speed can be up to 30 m/min, but for films as thick as 1 mm the speed is less: about 1 m/min. Control of the laser profile allows simultaneous welding and cutting (the “cut-seal process”). If one of the two sheets being joined is colored and the other is transparent, the colored sheet should be placed furthest from the beam.

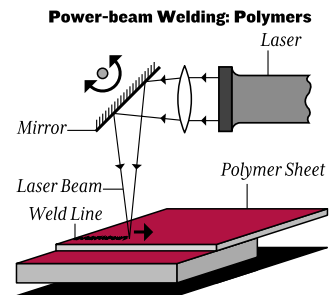
Power-beam Welding, continued

The Economics The cost of power-beam equipment is high, and – for e-beam welding – cycle times are long because of the need to evacuate the vacuum chamber. But despite this, the speed and controllability compensate, making both attractive in large-scale manufacturing. When production volumes are large as in the automotive industry and the microelectronics field, the high investment can be amortized; and the high welding speed, single pass welding, and freedom from the need for secondary operations make the process economic.

Typical Products Electron-beam welding is used extensively to assemble gears and transmissions for automobiles, aircraft engines, and aerospace products. High capacity electron beam equipment is used for pressure vessels, nuclear and process plant, and chemical plant. Laser-beam welding is used where precise control is important: joining of microelectronic components and thin gauged parts like bellows and watch springs. Increasingly, the process has been adapted for automobile components – gears, transmission assemblies, aerospace, and domestic products. Laser welding of polymers: food packaging and the sealing of bio-medical materials and equipment. There is growing interest in its use for welding of PET and other polymers for structural use.

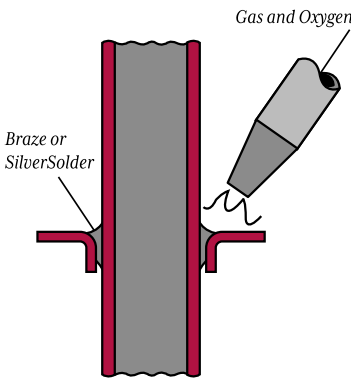
The Environment Electron beams generate X-rays, infrared and ultraviolet radiation. Laser beams are damaging – particularly to the eyes. Proper protection is essential for both, requiring strict safety procedures. But apart from this, the processes are attractive from an environmental standpoint: they are clean, involve no chemicals, and produce no waste.

Competing Processes Metals: resistance welding, threaded fasteners. Polymers: hot bar welding.



Attributes of Power-beam Welding: Polymers

Size of joint	Restricted
Maximum thickness, mm	
(direct heat)	0.1–1
(dye absorption)	1–10
Unequal thickness?	Limited
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	200–300



Attributes of Brazing

Size of joint	Unrestricted
Maximum thickness, mm	1-100
Unequal thickness?	Yes
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	450-600

Brazing

What Is It? When the components to be joined cannot tolerate the temperatures required for welding, the alternatives are brazing, soldering, mechanical fasteners, or adhesives. Brazing is the hottest of these. In brazing a low melting temperature metal is melted, drawn into the space between the two solid surfaces by capillary action, and allowed to solidify. Most brazing alloys melt above 450 C but below the melting temperature of the metals being joined. The braze is applied to the heated joint as wire, foil, or powder, coated or mixed with flux, where it is melted by a gas-air torch, by induction heating, or by insertion of the components into a furnace; the components are subsequently cooled in air.

Joint Type All joint geometries, particularly butt, scarf, and lap.

Design Notes Almost all metals can be joined by some variant of brazing, provided they have melting temperatures above 650 C. The process can join dissimilar metals even when they have different melting temperatures. Brazing is easily adapted to mass production (cheap bicycles are brazed) and the joint is strong, permanent, and durable. A large joint area is good – it compensates for the relatively low strength of the brazing metal itself.

Joints need a clearance of 0.02-0.2 mm to allow a good, strong bond to form. Ceramics can be brazed if the mating surfaces are first metalized with copper or nickel.

Technical Notes Brazing alloys are designed to melt at modest temperatures (450-600 C), to wet the surfaces being brazed (often by forming an alloy with the surfaces), and to be very fluid. The most common are those based on brass-like compositions (hence the name) and on silver. Brazing brass (0.6 Cu, 0.4 Zn) and bronzes (the same with 0.0025 Mn, 0.01 Fe, and 0.01 Sn) are used to join steel, stainless steel, copper, and nickel; silver solders (0.3-0.6 Ag, 0.15-0.5 Cu + a little Zn) are even better for the same metals. Fluxes play an important role in removing surface contamination, particularly oxides, and in improving wettability by lowering surface tension.

The Economics The equipment and tooling costs for brazing are low. Torch brazing requires a certain skill; furnace brazing can be automated, requiring no skilled labor. The process is economical for small runs, yet allows high production rates when automated.

Typical Products Brazing is widely used to join pipe work, bicycle frames, fittings and to repair castings and assemble machine parts.

The Environment Brazing generates fumes, and some fluxes are toxic – good ventilation and clean-up are important. Otherwise, brazing has a low environmental impact; the metals involved are non-toxic.

Competing Processes Adhesives, soldering, threaded fasteners.

Soldering

What Is It? Soldering is low-temperature brazing; or – another analogy – it is gluing with metal. It uses alloys that melt below 450 C. Soldered joints are less strong than brazed joints – more like an adhesive – but the equipment needed to make them is simpler and the temperatures reached by the component are much lower, an essential for the assembly of electronic equipment. Soldering can be applied in the same way as braze, or – more like an adhesive – by pre-coating (“tinning”) the metal surfaces to be joined before assembling and simply heating them with a torch, an electric soldering iron, or an array of infrared lamps. In re-flow soldering, the components are heated by vapor from a boiling fluorinated hydrocarbon that condenses on components, releasing latent heat, and giving rapid, uniform heating.

Joint Type All joint geometries, particularly lap, scarf, and sleeve.

Design Notes Solders are electrical conductors – it is this that gives them their prominence in the electronics industry. From a mechanical viewpoint they are soft metals; it is the thinness of the soldered joint that gives it high tensile strength, but the shear strength is low (below 2 MPa) thus soldered joints should have an area large compared with the load-bearing section (as in lap or sleeve joints), or be given additional mechanical strength (as in locked-lap joints). Solders can join dissimilar materials of very different thickness and size.

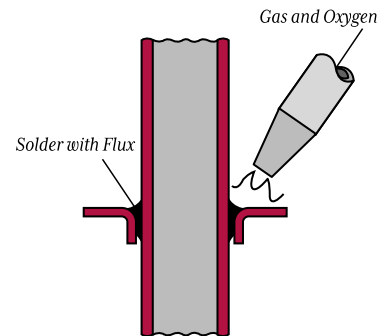
Technical Notes Solders are alloys of low melting temperature metals – lead, tin, zinc, bismuth, cadmium, indium. The lowest melting combination of any two metals is the “eutectic” composition; lead-tin solders for electrical connections have this composition (0.6 Sn, 0.4 Pb). Lead-tin solders for other applications range in composition from 0.2 to 0.6 Sn. Tin-antimony solders are used for electrical connection. Indium-tin solders are used for glass to metal joints. Soldering requires fluxes. Some are merely solvents for grease, cleaning the surface; others are acids and must be removed after the joint is made or they cause trouble.

Typical Products Solders are widely used to make electrical connections, to create printed circuit boards and attach logic chips to them, for domestic pipe-work, automobile radiators, precision parts in jewelry.

The Economics Like brazing, soldering is a flexible process, allowing high production rates, yet is also economic for small batches. The costs of equipment and tooling are low, and no great skills are required.

The Environment Now we come to it. Heavy metals – lead and cadmium in particular – have a bad eco-reputation. There is mounting pressure to replace them. Alternatives are emerging, but they cost more and are harder to use.

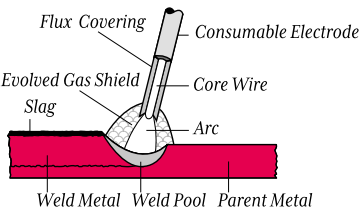
Competing Processes Brazing; adhesives; threaded fasteners.



Attributes of Soldering

Size of joint	Unrestricted
Maximum thickness, mm	1–10
Unequal thickness?	Yes
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	150–450

Torch Welding (MMA or SMA)



Attributes of Torch Welding

Size of joint	Unrestricted
Maximum thickness, mm	1-100
Unequal thickness?	Limited
Join dissimilar materials?	No
Impermeable?	Yes
Processing temp., C	1500-1700

What Is It? Torch welding, also known as “manual” or “shielded metal arc” (MMA or SMA) welding, is the most important general-purpose welding and surfacing method using low-cost equipment. In it, an electric arc is established between a flux-coated consumable rod (an electrode) and the component. The flux coating decomposes to give a gas shield; the slag that forms over the weld pool prevents the metal from oxidizing. Appropriate choice of metal and flux allow the process to be used for a wide variety of applications, though they are almost exclusively limited to ferrous alloys.

Joint Type All joint geometries.

Design Notes MMA is easy to use and very flexible, making it a prime choice for one-off or low volume production; but – because it cannot be automated – it is not an appropriate mass production process. Distortion caused by thermal expansion is minimized by designing symmetry into the weld lines and balancing the welds around the neutral axis of the structure. Weld lines are best designed to be straight or have simple contours, and the joint must be designed to allow access to the weld torch.

Technical Notes Carbon, low alloy and stainless steels, cast irons, and certain nickel alloys can be joined by MMA welding. Dissimilar materials are difficult to weld. The weld rod is consumed, providing filler metal to the weld; but when it is used up it has to be replaced, disrupting the welding process and causing random stresses in the joints. The flux must be removed in a cleaning operation between each weld pass.

The Economics MMA welding is a versatile, low-cost process, easily transported, but it cannot easily be automated because of the limited length of each electrode.

Typical Products MMA is used to join pressure vessels, structural steel work, pipe-work, to attach stiffeners to structures in ship building and in general engineering.

The Environment Welding fumes can present health hazards, and radiation from the weld can damage eyesight. Good ventilation and the use of welding masks and tinted goggles overcome these problems.

Competing Processes MIG and TIG welding.

MIG Welding

What Is It? Gas metal arc (MIG) welding is one of the Big Three heavy-duty welding processes (together with Torch and TIG). The electrode here is a bare wire, with no flux. The flux is replaced by a stream of inert gas, which surrounds the arc formed between the consumable wire electrode and the component; the wire is advanced from a coil as the electrode is consumed. The real advantages over torch welding are that there is no flux or slag, giving a cleaner weld – and that it can be automated. But there is a penalty: because the process needs gas, it is more expensive and less portable. Nonetheless, MIG is considered to be the most versatile of all arc welding processes.

Joint Type Butt, lap.

Design Notes If you want high-quality welds in aluminum, magnesium, titanium, stainless steel, or even mild steel, MIG welding is the process to choose. It is best for fillet welds through an adaptation – MIG spot welding – and lends itself well to lap joints. Distortion by thermal expansion is minimized by designing symmetry into the weld lines, and balancing the welds around the neutral axis of the structure. Weld lines are best designed to be straight or have simple contours, and the joints are designed to allow access for the weld torch.

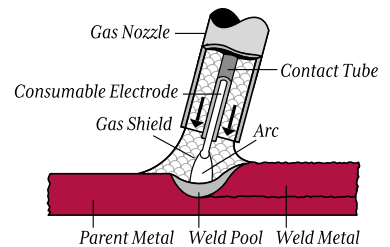
Technical Notes Most common metals and alloys except zinc can be welded using MIG; electrode wire (the filler material) is available for welding all of these. The shielding gas is usually argon, helium, carbon dioxide, or a mixture of these – it is chosen to suit the material being welded. The process produces uniform weld beads that do not require de-slagging, making it suitable for mechanization and operation by welding robots. MIG can make most joint geometries and can be done in most orientations, but is most efficient when flat and horizontal.

The Economics Equipment costs are moderate, tooling costs are low. MIG welding is more expensive than Torch welding because of the cost of the inert gas, but it is rapid and requires less labor.

Typical Products MIG welding is used throughout the industry in both manual and automatic versions, particularly ship building, structural engineering, process plant and electrical engineering, domestic equipment, and the automobile industry. It is indispensable for welding difficult, non-ferrous metals such as aluminum, magnesium, and titanium.

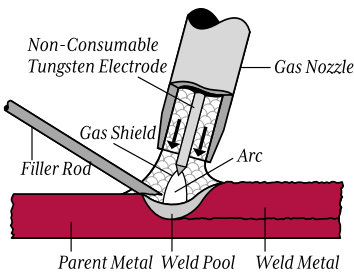
The Environment Health hazards depend on the composition of the electrode and component; both appear as airborne fume during welding. Radiation from the weld can be harmful to the eye, requiring that a welding helmet and tinted safety goggles must be worn.

Competing Processes Torch welding, TIG welding.



Attributes of MIG Welding

Size of joint	Unrestricted
Maximum thickness, mm	1–100
Unequal thickness?	Limited
Join dissimilar materials?	No
Impermeable?	Yes
Processing temp., C	600–2000



Attributes of TIG Welding

Size of joint	Unrestricted
Maximum thickness, mm	0.2– 10
Unequal thickness?	Limited
Join dissimilar materials?	No
Impermeable?	Yes
Processing temp., C	600–2000

TIG Welding

What Is It? Tungsten inert-gas (TIG) welding, the third of the Big Three (the others are Torch and MIG) is the cleanest and most precise but also the most expensive. In one regard it is very much like MIG welding: an arc is struck between a non-consumable tungsten electrode and the work piece, shielded by inert gas (argon, helium, carbon dioxide) to protect the molten metal from contamination. But, in this case, the tungsten electrode is not consumed because of its extremely high melting temperature. Filler material is supplied separately as wire or rod. TIG welding works well with thin sheet and can be used manually, but is easily automated. Both penetration and deposition rates are much less than those of MIG welding, but precise control of the weld is easier.

Joint Type All joint geometries.

Design Notes Because the heating is de-coupled from the filler supply, greater control of weld conditions is possible. Thus, TIG welding is used for thin plate and for precision assemblies, made of almost any metal. Clean surfaces and well-prepared joints are important. It is principally used for thin sections and precisely made joints.

Technical Notes TIG welding produces very high-quality welds on metals such as aluminum, magnesium, titanium, stainless steel, and nickel; cast iron and mild steel are also easily welded. The arc is started by a high frequency AC discharge to avoid contaminating the tungsten electrode; it is subsequently maintained by a DC current or a square wave AC current, which gives greater control of penetration.

The Economics The equipment is more expensive and less portable than Torch, and a higher skill level is required of the operator. But the greater precision, the wide choice of metals that can be welded and the quality of the weld frequently justify the expense.

Typical Products TIG welding is one of the most commonly used processes for dedicated automatic welding in the automobile, aerospace, nuclear, power generation, process plant, electrical and domestic equipment markets.

The Environment TIG welding requires the same precautions as any other arc welding process: ventilation to prevent inhalation of fumes from the weld pool, and visors or colored goggles to protect the operator from radiation.

Competing Processes Torch and MIG welding.

Resistance Welding

What Is It? The tungsten filament of a light bulb is heated, by resistance, to about 2000 C. That is more than enough to melt most metals. Resistance welding relies on localizing the electric current I (and thus the I^2R heating) where heating is desired: at the interface. In resistance spot welding, the overlapping sheets are pressed between water-cooled electrodes. The current-pulse generates heat; the cooled electrodes chill the surfaces, localizing the heat in the interface between the sheets where the metal melts and welds. Projection spot welding uses an additional trick – a pre-formed pimple on the face of the joint – to confine the current path and further localize the heating; a clever idea, because it extends the use of the method to forgings, castings, and machined components and makes it faster because several welds can be made at the same time. In seam resistance welding the electrodes are water-cooled wheels, between which overlapping sheets are rolled to give a seam weld.

Joint Type Butt and lap.

Design Notes Resistance welding has many advantages over rivets or screw fasteners: it is faster, easily automated, requires no drilling or punching and no fluxes or fillers; and it gives products that are lighter. Joint design must allow for access to electrodes.

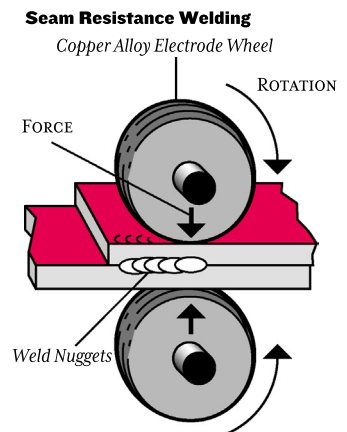
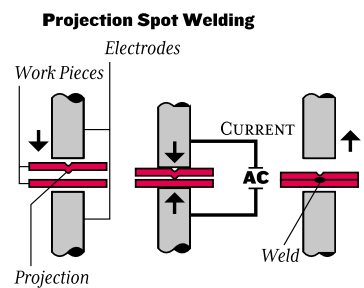
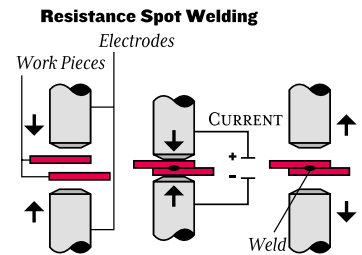
Technical Notes Resistance welding is commonly used for steels of all grades, aluminum, magnesium, brass, and cast iron. Electrodes are made of low resistance copper alloys and are hollow to allow water cooling. Resistance spot welding rates are typically 12–180 welds/min; projection spot welding rates are greater.

The Economics The capital cost of equipment is medium; high if automated. But the process is fast, reliable, lends itself to automation, and requires no post-weld treatments.

Typical Products The really big-time users of resistance welding are the automobile and domestic appliance industries. In aircraft structures it is used for assembling doors, fuselage stringers, outer skins, decking, ribs, and seat frames. The electronics industry makes extensive use of miniaturized spot welding for assembling circuitry. Seam resistance welding is used for water or gas-tight assemblies: fuel tanks for vehicles, duct work, drums, and cans.

The Environment The heat and the flash of welding require normal precautions – face-shield, goggles – but otherwise the environmental burden is minimal.

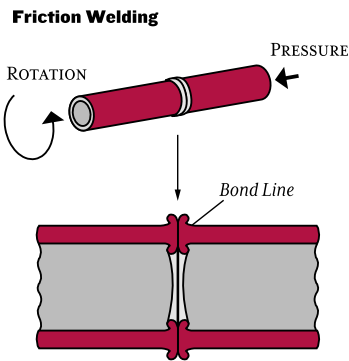
Competing Processes Threaded fasteners, adhesives, Power-beam welding.



Attributes of Resistance Welding

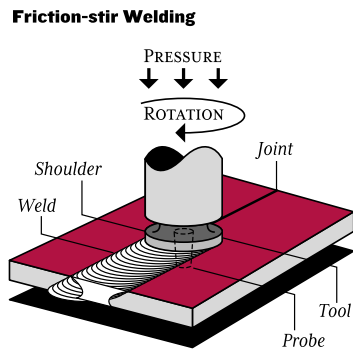
Size of joint	Unrestricted
Maximum thickness, mm	0.1–10
Unequal thickness?	Limited
Join dissimilar materials?	Yes
Impermeable?	If seam
Weld	
Processing temp., C	600–2000

Friction Welding



What Is It? When there is friction between two people, heat may be generated but they rarely bond. Materials are different: rub them together and there's a good chance they'll stick. In friction welding, one component is rotated or vibrated at high speed, forced into contact with the other, generating frictional heat at the interface, and – when hot – the two are forged together. In direct drive friction welding, the motor is connected to the work piece and starts and stops with each operation. In inertial friction welding, the motor drives a fly wheel that is disconnected from the motor to make the weld. In friction stir welding a non-consumable rotating tool is pushed onto the materials to be welded. The central pin and shoulder compact the two parts to be joined, heating and plasticizing the materials. As the tool moves along the joint line, material from the front of the tool is swept around to the rear, eliminating the interface. The weld quality is excellent (as good as the best fusion welds), and the process is environmentally friendly.

Joint Type Butt.



Design Notes Friction welding gives clean, high-quality joints between a wide variety of metals – particularly metal matrix composites can be joined in this way. Dissimilar materials can be joined: stainless steel and aluminum for instance. No melting is involved so no protective flux or gas are needed. Linear or orbital motion allows non-circular shapes to be joined.

Technical Notes For small components, rotational speeds of up to 80,000 rpm and a few kilograms load are used; for very large components the rotational speed is as slow as 40 rpm with thousands of kilograms forging load. Weld times range from 1–250 seconds.

The Economics The capital cost of equipment is high, but tooling costs are low. The process is fast and can be fully automated.

Typical Products Friction welding is widely used to join automobile components, agricultural machinery, and for welding high-speed steel ends to twist drills. It is the best way of attaching forgings to shafts or bars, or hub bearings to axles.

The Environment Friction welding is clean and energy-efficient.

Competing Processes Torch welding, MIG welding, TIG welding, ultrasonic welding.

Attributes of Friction Welding

Size of joint	Restricted
Maximum thickness, mm	1–100
Unequal thickness?	Yes
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	400–1200

Diffusion and Glaze Bonding

What Are They? Joining ceramics poses problems because they are hard and brittle. Mechanical fasteners generally require holes, and create high clamping forces and stress concentrations. Conventional welding is impractical: the melting temperatures of ceramics are very high and residual stresses lead to cracking. Adhesives stick to ceramics, but few are reliable above 300 C, where ceramics are often used. Two processes bypass these difficulties: diffusion and glaze bonding. In diffusion bonding the surfaces to be joined are cleaned, pressed into close contact, and heated in vacuum or a controlled atmosphere. Solid-state diffusion creates the bond, which is of high quality, but the process is slow and the temperatures are high. Diffusion bonding is used both for ceramics and metals – among the metals: titanium, metal matrix composites, and certain steels and copper-based alloys are particular candidates. Glaze bonding depends on the fact that molten glass wets and bonds to almost anything. To exploit this, the surfaces to be joined are first coated with a thin layer of finely-ground glass slurry, with the composition chosen to melt at a temperature well below that for diffusion bonding, and with maximum compatibility between the two surfaces to be joined. A small pressure is applied across the interface and the assembly is heated, melting the glass and forming a thin, but strong bonding layer.

Joint Type All joint types.

Design Notes The processes allow differing materials to be joined: ceramic to ceramic, ceramic to glass, metal to ceramic, metal to metal. Glaze bonding is particularly versatile: tailoring the glass to match the requirements of melting temperature and thermal expansion allows bonds between metal and ceramic.

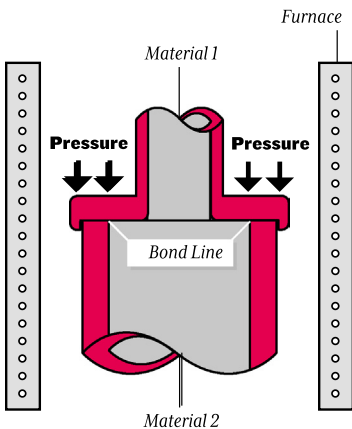
Technical Notes To make materials bond by diffusion requires temperatures above three-fourths of their melting temperature, and a modest pressure to keep the surfaces together. Ceramics melt at very high temperatures – so the processing temperatures are high. Glaze bonding overcomes this by creating an interfacial layer that bonds closely to both surfaces but melts at a much lower temperature.

The Economics These processes are energy-intensive and slow. But for some material combinations this is the only choice.

Typical Products For metals: assembling titanium aircraft panels, and smaller items where dissimilar metals must be joined. For ceramics and glasses: bonding these to each other and to metals.

The Environment The environmental impact is low except in one regard: energy demand is high.

Competing Processes For ceramics: threaded fasteners, adhesives. For metals: threaded fasteners, beam welding.



Attributes of Diffusion and Glaze Bonding


Size of joint	Restricted
Maximum thickness, mm	1–100
Unequal thickness?	Yes
Join dissimilar materials?	Yes
Impermeable?	Yes
Processing temp., C	600–1800

Surface Profiles

Almost every component of a product has some sort of surface process applied to it. Surface processes enhance the thermal, fatigue, friction, wear, corrosion, or aesthetic qualities of the surface, leaving the bulk properties unchanged. Economically they are of great importance, extending life, allowing materials to be used in increasingly harsh service conditions, imparting multi-functionality (for example – by creating a corrosion resistant surface on a tough, but chemically reactive substrate, or a thermally insulating surface on a strong, but metallic substrate) and, of course, creating much of the visual and tactile features of a product.

The choice of a surface process depends on the material to which it will be applied and the function it is to perform. The processes used to etch the surface of glass differ in obvious ways from those used to texture polymers; less obviously, paints and electro-coatings, too, are often material-specific. The pages that follow profile ways of treating surfaces, describe the processes and their functions, and list the materials to which they can be applied. They cover the most common processes used to create the visual and tactile qualities of products.

More information can be found in the sources listed under “Further Reading.”



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Further Reading

There is a confusing diversity of surface processes. Some (such as painting) are applicable to many materials; others (like electro-less plating) are limited to one or a few. Selection is not easy, particularly as there is, at present, no single information source that allows comparison of the full range. The major contributions to systematic surface process selection derive from sources that, generally speaking, focus on one class of process or one class of material: painting, for instance ([Roobol, 1997](#)); coating technology ([Gabe, 1983](#); [Rickerby and Matthews, 1991](#); [Grainger and Blunt, 1998](#)); of heat treatment ([Morton, 1991](#); [Sudarshan, 1989](#)); of corrosion ([Strafford et al., 1984](#); [Gabe, 1983](#)); or electro-deposition ([Canning, 1978](#)). A lesser number attempt a broader review ([ASM, 1982](#); [Poeton, 1999](#); [CES, 2002](#)), but are far from comprehensive. Some of the sources we have found helpful are listed below. Much more information can be found on the Internet, though it is uneven in content and quality. We have made extensive use of the Internet, of information from companies, and of the books listed below in compiling the profiles contained in this section.

ASM (1982) "ASM Metals Handbook Volume 5: Surface Cleaning, Finishing, and Coating," Ninth edition, American Society for Metals, Materials Park, OH, USA. (The volume of this distinguished handbook-set devoted to surface engineering.)

Bralla, J.G. "Handbook of Product Design for Manufacturing," Second edition," McGraw-Hill, New York, NY, USA. ISBN 0-07-007139. (The Bible – a massive compilation of data for manufacturing processes, authored by experts from different fields and edited by Bralla.)

Canning, W. (1978) "The Canning Handbook on Electroplating," W. Canning Limited, Gt. Hampton St., Birmingham, UK.

CES 4 (2002) "The Cambridge Engineering Selector," Version 4, Granta Design, Cambridge, UK, www.grantadesign.com.

Gabe, D.R. (1983) "Coatings for Protection," The Institution of Production Engineering, London, UK.

Grainger, S. and Blunt, J. (1998) "Engineering Coatings, Design and Application," second edition, Abington Publishing, UK. ISBN 1-85573-008-1. (A monograph aimed at technical engineers detailing processes for enhancing wear and corrosion resistance of surfaces.)

Morton, P.H. (1991) "Surface Engineering and Heat Treatment," The Institute of Metals, London, UK.

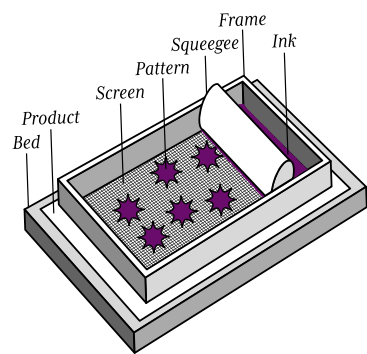
Poeton (1999) "The Poeton Guide to Surface Engineering," www.poeton.co.uk/pands/sface/.

Rickerby, D.S. and Matthews, A. (1991) "Advanced Surface Coatings: A Handbook of Surface Engineering," Chapman and Hall, New York, NY, USA.

Roobol, N.R. (1997) "Industrial Painting, Principles and Practice," second edition, Hanser Gardner Publications, Cincinnati, OH, USA. ISBN 1-56990-215-1. (A comprehensive guide to painting and resin coating.)

Strafford, K.N., Dalta, P.K. and Googan, C.G. (1984) "Coatings and Surface Treatment for Corrosion and Wear Resistance," Ellis Horwood Limited.

Sudarshan, T.S. (1989) "Surface Modification Technologies," Marcel Dekker, Inc., New York, NY, USA.



Attributes of Screen Printing

Surface hardness, Vickers	5-10
Coating thickness, μm	10-100
Curved surface coverage	Poor
Processing temp., C	15-25

Screen Printing

What Is It? Walk down any street and you will see examples of screen printing: displays and posters advertising products in shops; buses with ads on their sides; badges and control panels on computers and stereo equipment; sports bags and T-shirts; and even the Pop Art creations of Andy Warhol. Screen printing has its origins in Japanese stenciling, but the process that we know today stems from patents taken out by Samuel Simon of Manchester at the turn of the last century. He used silk stretched on frames to support hand painted stencils, a process also used by William Morris to create his famous wallpapers and textile prints. During the First World War in America screen printing took off as an industrial printing process; but it was the invention of the photographic stencil in the 1930s that revolutionized the process. It is now a \$5 billion per year industry.

Functions Color, reflectivity, texture.

Design Notes The process can be applied to polymers, glass, metals, wood, textiles, and of course paper and board. Flat and cylindrical objects can be printed. Multiple colors can be printed, but each requires a separate screen.

Technical Notes The screen is a wooden or aluminum frame with a fine silk or nylon mesh stretched over it. The mesh is coated with a light-sensitive emulsion or film, which – when dry – blocks the holes in the mesh. The film is exposed to the image or pattern to be printed using ultraviolet light, hardening it where exposed. The screen is washed, removing the emulsion where it was not hardened, leaving an open stencil of the image that was printed onto it. The screen is fitted on the press, the product to be printed is placed under the screen, and the topside of the screen is flooded with ink. A rubber blade gripped in a wooden or metal handle called a squeegee (not unlike a giant windscreen wiper) is pulled across the top of the screen; it pushes the ink through the mesh onto the surface of the product. To repeat the process the squeegee floods the screen again with a return stroke before printing the next impression. Epoxy inks give protection against scratching and can be used with products that attack standard enamel inks.

The Economics The capital cost of the equipment is low. The process is economic for small runs and one-color printing. Each additional color adds to the cost because it is applied separately, and requires registration.

Typical Products Posters, stickers, ticketing, shelf strips, banners, exhibition panels, ring binders, mouse-mats, site boards, signs, T-shirts, control panels, and badges for computers.

The Environment The chemicals, particularly the cleaning fluids, can be volatile and toxic, requiring good ventilation and operator protection.

Competing Processes Solvent- and water-based painting; pad printing; cubic printing.

Pad Printing

What Is It? Pad printing is a little like printing with rubber stamps; instead of rubber, the image is cut into a steel or copper plate, from which it is lifted by a rubber pad. It is used as a decorating process for irregular shapes, and for those shapes which cannot be easily printed by silk screen. The steps are as follows. (1) The image to be transferred is etched into a printing plate commonly referred to as a cliché. The cliché is flooded with ink and wiped, leaving ink only in the image area. As solvents evaporate from the image area the ink's ability to adhere to the silicone transfer pad increases. (2) The pad is pressed onto the cliché lifting the ink. Solvents evaporate from the outer ink layer where it is exposed to the atmosphere, making it tackier and more viscous. (3) The pad is pressed onto the component to be decorated, conforming to its shape and depositing the ink. Even though it compresses considerably during this step, the contoured pad is designed to roll away from the substrate surface without smudging the image by sliding. (4) When the pad is pressed onto the product, the adhesion between the ink and substrate is greater than the adhesion between the ink and pad, resulting in complete transfer of the ink, leaving the pad clean and ready for the next cycle. Automatic methods, with several pads in series (transfer pad printing), allow cheap multi-color decoration. Manual machines are used for low production volumes; for these, multi-color prints require separate steps and set-up time.

Functions Color, reflectivity, texture.

Design Notes The advantages of pad printing are the ability to print on irregular surfaces (such as a golf ball) and to print wet on wet multi-colors. Its excellent quality of detail makes pad printing attractive for flat items. Pad printing is limited to relatively small images compared to screen printing—usually less than 0.1 m². Large opened areas can be difficult to cover, requiring special, screened clichés.

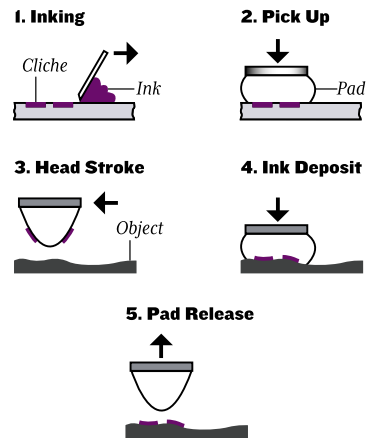
Technical Notes Polymer, glass, and metal products can all be printed. Three-dimensional, irregular shapes are possible. The inks are pigmented resins suspended in organic thinners.

The Economics Capital and tooling costs are low. The process is fast, and the product can be handled immediately after printing.

Typical Products Cups, pens, glass frames, lighters, golf balls.

The Environment Thinners can give toxic fumes, requiring ventilation.

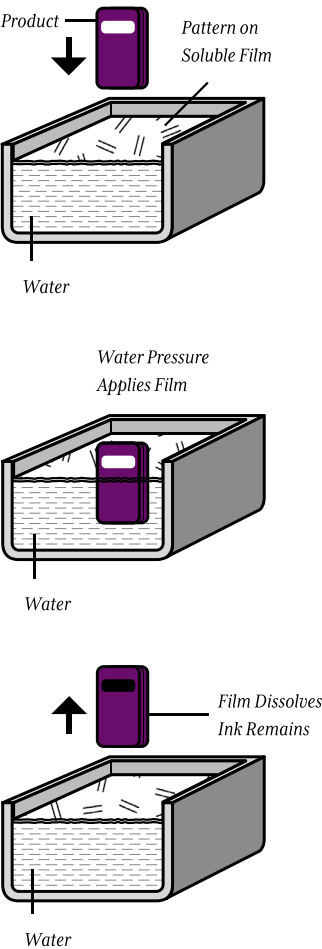
Competing Processes Solvent- and water-based painting; screen printing; cubic printing.



Attributes of Pad Printing

Surface hardness, Vickers	5–10
Coating thickness, μm	6–10
Curved surface coverage	Good
Processing temp., $^{\circ}\text{C}$	15–30





Cubic Printing

What Is It? Transfers are familiar to every child – a painless way of applying images to paper, to products, and even to yourself. The image is printed on a thin, water-soluble film; when floated on water, the image floats free and can be transferred to the product to which it sticks. Cubic printing uses the same principle, scaled-up and made commercially viable. The film and its image are floated on the surface of a water tank. The product is immersed in the tank, where the pressure of the water presses the image onto the surface of the component.

Functions Color, reflectivity, texture.

Design Notes Cubic printing is very versatile; complex, curved shapes can be printed and the image can be multi-colored. Registration is difficult, so the image is usually applied in a single operation, and designed so that precise registry is not necessary.

Technical Notes The pattern or design is printed on a water-soluble film. The film, specially treated to activate the inks, is floated onto the water, where it dissolves, leaving the decoration inks on the water surface. The component to be decorated is pressed down into the water to effect the transfer. The inks flow on the surface of the object, decorating it in three dimensions. A transparent topcoat is applied to protect the printed surface. Polymer, ceramic, glass, metal, and wood products can all be printed. Printing on three-dimensional and irregular shapes is possible.

The Economics Capital and tooling costs are low. The component must be dried and given a finishing coat, making it relatively slow.

Typical Products Automotive: dash panels, console, steering wheel, shift knobs, spoilers, bumpers, visor. Sports equipment: tennis racket, fishing reels, gun stocks, helmets, golf clubs, sunglasses, bikes. Computer products: monitor panel, keyboards, mice, PC note books, digital cameras, printers. Appliances: TV, refrigerators, washer-dryer, coffee maker, microwave, stereo equipment. Kitchen Products: canisters, silverware, glass stems, bowls, pitchers, salt and pepper shakers. Furniture: end tables, coffee tables, door knobs, picture frames, tissue holders, clocks.

The Environment Cubic printing presents no significant environmental problems.

Competing Processes Solvent- and water-based painting; silk screen printing; pad printing.

Attributes of Cubic Printing

Surface hardness, Vickers	5-10
Coating thickness, μm	6-10
Curved surface coverage	Good
Processing temp., C	15-30

Hot Stamping

What Is It? Next time you see a book with imprinted gold lettering on its cover, think of hot stamping. It is a dry process for permanently applying a colored design, logo, text, or image. It is best known as a method of applying metallic gold or silver lettering or decoration. A heated metal die (250–300 C) is pressed against a colored carrier foil and the component being printed. The hot stamp is created when the raised surface of the die contacts the foil and transfers the colored film on the face of the foil to the product being printed. The pressure from the die creates a recess for marking, which protects the stamped letter from abrasion, and heat makes the marking medium adhere to the product.

Functions Color, reflectivity, texture.

Design Notes Block lettering can be hot stamped on either raised or flat areas. For irregular surfaces, a silicone plate is used to transmit heat and pressure to the foil. A range of decorating finishes is available, including metallic foils, wood grain finishes, and multi-colored graphics. The process can be applied to polymers, wood, leather, paper, vinyl, mylar, and textiles such as polyester and acetates, and – less easily – to painted metal. Decoration is permanent and resists peeling, scratching, and abrasion.

Technical Notes Hot stamping dies are made from magnesium, brass, or steel. Inexpensive photo-etched dies work well for prototype or short runs on flat areas; dies for long production runs are deep-cut from either brass or steel. Foils are made in four plies: a thin film carrier, generally polyester, a release coating, a decorative coating – pigment or metallic – and an adhesive specific to the substrate material.

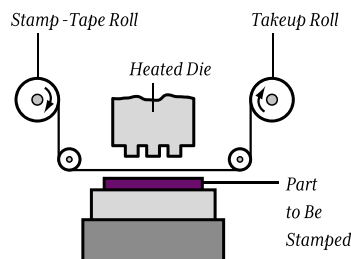
The Economics The equipment costs are low. Hot stamping with polymer or aluminum foil is inexpensive; gold foil can be expensive. Components can be handled and packed immediately. Minimal set-up time allows users to change graphics and colors as needed by simply changing a dry roll of foil or transfers.

Typical Products Retail and cosmetics packaging, book binding, automotive finishing, commercial printing, consumer goods, computer casings, and tape cassettes.

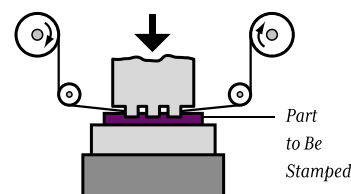
The Environment No ink mixing or clean-up involving volatile organic solvents (VOCs) is required. The die is hot, but otherwise the process is pollutant-free.

Competing Processes Solvent- and water-based painting; pad printing; cubic printing.

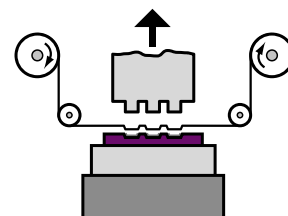
1. Set-up



2. Stamping

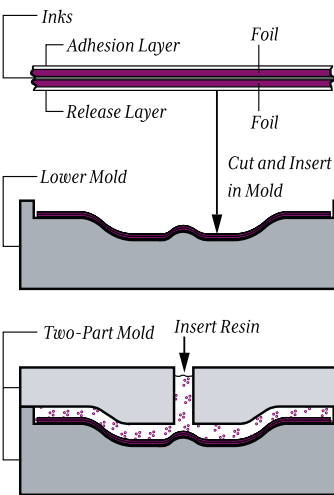


3. Finish



Attributes of Hot Stamping

Surface hardness, Vickers	5–50
Coating thickness, μm	1–50
Curved surface coverage	Poor
Processing temp., C	150–300



Attributes of In-mold Decoration

Surface hardness, Vickers	5-15
Coating thickness, μm	10-500
Curved surface coverage	Avg. to Good
Processing temp., C	125-200

In-Mold Decoration

What Is It? In-mold decoration (IMD) allows accurately registered colors, designs, and print to be applied to injection molded components without any secondary processing. The image, which can be full color, is printed onto a polyester or polycarbonate film called the “foil.” If the product is flat or mildly curved, the foil is fed as a continuous strip, or cut and placed directly in the mold. If true three-dimensional components are to be made, the foil is first thermally molded to the shape of the component, then placed in the mold cavity. Hot liquid resin is injected behind the foil, bonding its surface to the molding resin and forming an integrally decorated component.

Functions Color, texture, patterning, printing; resistance to abrasion.

Design Notes The figure shows the build-up of a more complex foil. The decorative coatings are applied to the foil in reverse order: the release coating directly onto the foil, then the various color coatings, and finally the adhesive layer. By printing the graphics on the second surface, the design is held within two thin polymer layers, protecting it from wear and tear. Change of decoration simply requires a change of foil, without changing the mold or the material.

Technical Notes In the continuous IMD process modified hot-stamping foils are passed from a roller into the injection mold. On injection, the pressure and temperature of the melted polymer releases the carrier film, bonds it to the molding, and presses it into the die-cavity, thereby molding the two-dimensional film into a three-dimensional geometry; however, the pattern can sometimes become distorted. In the discrete process, the foil is cut and placed in the mold. Complex shapes require that the foil is first thermally molded to the approximate shape of the mold cavity before insertion. Most thermoplastics – including polycarbonate, but not, however, polyethylene – can be decorated by IMD without problems.

The Economics IMD is simple and fast, and it reduces the number of steps in the manufacturing process, allowing the low-cost decoration of moldings that previously required a separate, costly, hot-stamping process, and it offers a greater range of graphics and colors.

The Environment IMD complies with the stringent environmental standards of the automotive industry. Recycled polymers can be used, as long as they have no gross contamination. The mold resin and the film can both be of the same material type, aiding recyclability.

Typical Products Mobile phone front and back covers, keypads, lenses, computer terminals, automotive heater controls, dashboards, toggle switches, credit cards.

Competing Processes Hot stamping, silk screen printing; cubic printing; pad printing.



Vapor Metalizing

What Is It? Mirrors used to be made by a complex process involving silver dissolved in mercury. Today they are made by PVD metalizing, a process in which a thin coating of metal – usually aluminum – is deposited from a vapor onto a component. The vapor is created in a vacuum chamber by direct heating or electron-beam heating of the metal, from which it condenses onto the cold component, much like steam from a hot bath condensing on a bathroom mirror. In PVD metalizing there is no potential difference between vapor source and component. In ion plating the vapor is ionized and accelerated by an electric field (the component is the cathode, and the metalizing source material is the anode). In sputtering argon ions are accelerated by the electric field onto a metal target, ejecting metal ions onto the component surface. By introducing a reactive gas, compounds can be formed (Ti sputtering in an atmosphere of N_2 , to give a hard coating of TiN, for instance).

Functions Color, reflectivity, texture; hardness, wear; electrical conduction; protection against aqueous corrosion and by organic solvents.

Design Notes Metalizing is widely used to give a reflective metallic finish on bulk and film polymers, metal, glass, and ceramic.

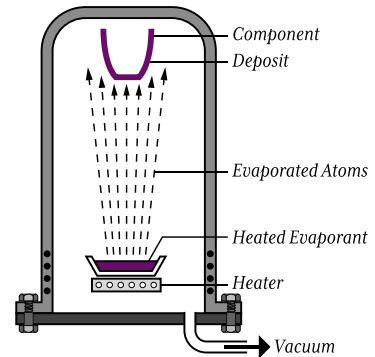
Technical Notes Clean surfaces are essential. Aluminum, copper, nickel, zirconium, and other metals can be deposited.

The Economics The capital cost is high, the tooling cost low. For aesthetics, PVD metalizing is preferred to electro-plating for polymers and ceramics because of its speed, quality, and absence of unpleasant chemicals.

Typical Products Automotive trim, household appliances and kitchenware, door and window hardware, bathroom fixtures, printed circuit boards.

The Environment High volume production, good quality and cleanliness – particularly the absence of unpleasant chemicals – makes this an attractive process from an environmental standpoint.

Competing Processes Electro-plating; electro-less plating.



Attributes of Vapor Metalizing

Surface hardness, Vickers 10–40

Coating thickness, μm 1–80

Curved surface coverage Avg. to Good

Processing temp., C 18–120

Electro-Plating

What Is It? When, in 1800, Alessandro Volta discovered how to make an electric battery, he unleashed the development of electro-chemistry. By 1806 Humphrey Davy, prolific inventor, had developed ways of plating metals from their salts and solutions – electro-plating. The component (cathode) and the metalizing source material (anode) are submerged in the aqueous electrolyte where a direct electrical current drives metal ions from the source to the component, creating a thin metal coating.

Functions Color, texture, reflectivity; corrosion resistance, wear resistance, providing electrical conductivity, and good electrical contact.

Design Notes Plating for aesthetic purposes has its origins in the silver and gold plating of tableware and cutlery (“Sheffield Plate”), and in chrome and nickel plating for shiny, durable surfaces. Most polymers can now be plated, but care must be taken to prevent the coating breaking or peeling in use. The ability to plate convoluted shapes depends on what is called the “surface coverage” of the plating bath. Some have very poor surface coverage, meaning that only flat or gently curved surfaces can be plated; others – often assisted by mysterious, proprietary additives to the plating bath – can plate complex shapes with reentrant features.

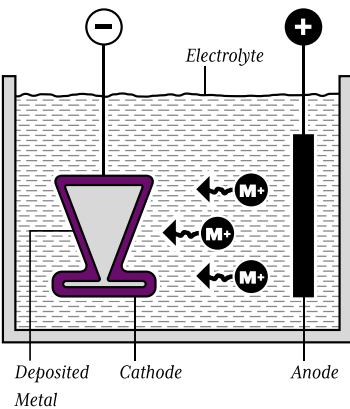
Technical Notes Almost any metal can be electroplated. Polymers (ABS, PET, ABS/polycarbonate, polyphenylene oxide, polysulfone, polypropylene, nylon, polyester, polyacetal, polystyrene, polycarbonate, epoxy/glass) and other non-electrically conductive materials must be first coated with an electrically conductive material. Cleaning and surface preparation are essential. The usual range of coating thickness is 1–50 microns, though thicknesses up to 1 mm are routine. Thicker coatings can generally be produced more cheaply or conveniently by other processes: thermal spraying, hot dipping, or cladding. The processing temperature is in the range 5–80°C. Coatability – the ease with which an electro-plating can be applied – increases in this order: aluminum, mild steel, brass, copper. Many electro-platings have internal stresses; these can be reduced by heat treatment.

The Economics The equipment cost for electro-plating is relatively high, but tooling costs are low. For thin deposits, particularly on small components or areas, large batch processing can make this a very competitive technique.

Typical Products A flavor for the immense range of applications of electro-plating, technical and aesthetic, can be tasted by scanning the list of materials that completes this profile.

The Environment Many electro-plating baths pose environmental and health hazards. Some contain disagreeable chemicals – those with cyanogens are downright nasty. Protection from chemical pollutants and toxic vapor requires special precautions, as does the disposal of the plating medium. Cadmium is toxic, and now banned as plating in many European countries. Alternatives to chromium plating, one of the more unpleasant of processes, are sought but not yet found. Nickel can cause allergies and should be kept away from skin contact. Such gloomy news is not, however, universal: electro-plating is widely used to coat with copper, gold, silver, tin, and zinc.

Competing Processes Solvent- and water-based painting; mechanical polishing; electro-polishing; electro-less plating, anodizing, vapor metalizing.



Attributes of Electro-plating

Surface hardness, Vickers	Depends on coating material
Coating thickness, μm	1–1000
Curved surface coverage	Depends on the bath
Processing temp., C	5–80



Image courtesy of IJD/International Design Trend Center

Aluminum

Aluminum electro-plating can substitute for hot dipped aluminum, but is infrequently used.

Brass

Brass lamps and trays, low-cost trim, interior automotive hardware, tubular furniture, household goods, toys, casket hardware, novelties, promote adhesion of rubber to steel.

Bronze

Bronze inexpensive jewelry, door plates, hardware, trophies, handbag frames, undercoat for nickel and chromium, bearing surfaces, tableware, household fixtures.

Cobalt

Cobalt alloy electroplates, mirrors, reflectors, applications where high hardness is required.

Co-Ni

Co-Ni magnetic recording, permanent magnet coating on memory drums in digital computers, electro-forming.

Copper

Copper undercoat (improved adhesion, prevention of hydrogen embrittlement), wire coatings, stop-off coatings during heat treatment and chemical milling, lubricant during drawing, thermally conductive coatings on cooking utensils, electro-forming.

Gold

Gold pen points, jewelry, watch and vanity cases, musical instruments, reflectors, name plates, eyeglass frames, bracelets, trophies, novelties, electrical contacts, springs, electronic parts, laboratory apparatus.

Nickel

Nickel base for thin chromium electroplates, trim for automobiles, appliances, business machines, and consumer goods, electro-forming, build-up of worn and mismachined parts.

Rhodium

Rhodium-resistant finish for costume jewelry, insignia, emblems, musical instruments, medical and surgical parts, laboratory equipment and optical goods, electrical contacts, reflectors and mirrors.

Silver

Silver tableware, candlesticks, cigarette lighters and musical instruments, bearings, surgical instruments, chemical equipment, electrical contacts.

Tin

Tin food and beverage containers, refrigerator evaporators, food and dairy equipment, hardware, appliance and electronic parts, copper wire, bearings.

Tin-Nickel

Tin-nickel cooking utensils, analytical weights, surgical instruments, watch parts, chemical pumps, valves and flow control devices, resistance to marine corrosion.

Tin-Zinc

Tin-zinc radio and television parts, cable connectors, relay assemblies, galvanic protection of steel parts contacting aluminum.

Zinc

Zinc appliances and automotive parts, finishing small parts (pipe couplings, bolts, nuts, rivets, washers, nails, hinges, hangers, hooks), electrical conduit pipes, silo and tie rods, screening, telephone exchange equipment.

Electro-Less Plating

What Is It? Electro-less plating is electro-plating without electricity. It relies instead on a difference in what is called electropotential when a metal is placed in a solution containing ions of another metal. Metal ions from the solution are deposited on the surface of the component by the action of a chemical reducing agent present in a metallic salt solution. In the case of electro-less plating of nickel (the most significant commercial application of the process), the salt is nickel chloride and the reducing agent is sodium hypophosphate. Once started the reaction can continue and there is no theoretical limit to the thickness of the coating. Electro-less plating is used when it is impossible or impractical to use normal electro-plating – when complex internal surfaces are to be plated, or when dimensional accuracy of the component is critical, for instance.

Functions Surface hardness and wear resistance; corrosion protection; electrical conductivity; magnetic permeability; aesthetics.

Design Notes Most metals and polymers can be coated. The coating is typically applied to non-metallics as a conductive base for subsequent electro-plating. The uniformity of the coating is good, even on components of very complex shapes.

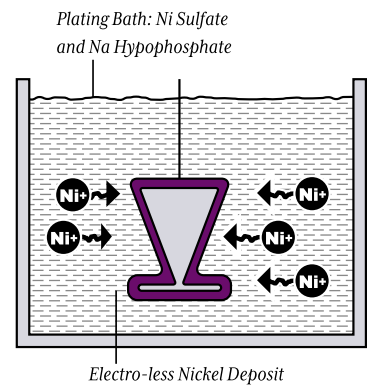
Technical Notes The main electro-less platings in current use are nickel (Ni, NiP, NiB, and nickel composite coatings containing SiC or PTFE) and copper. Ferromagnetic alloys Co-P, Ni-Co-P, Ni-Fe-P can be plated on magnetic tapes and disks. Special processing steps are needed for polymers because they are non-conductive and do not catalyze the chemical reduction of nickel; in this case adhesion results only from mechanical bonding of the coating to the substrate surface. To improve this, polymers are typically etched in acidic solutions or organic solvents to roughen their surfaces and to provide more bonding sites.

The Economics Electro-less plating is more costly than electro-plating: about 50% more for nickel plating. Deposition rates are much slower and chemical costs are higher; equipment and energy costs, however, are less. Despite these cost differences, the choice between the two processes is determined by physical rather than economical factors or production quantities.

Typical Products Heat sinks, bearing journals, piston heads, landing gear components, loom ratchets, radar wave guides, computer drive mechanisms, computer memory drums and disks, chassis, connectors, rotor blades, stator rings, compressor blades and impellers, chain saw engines.

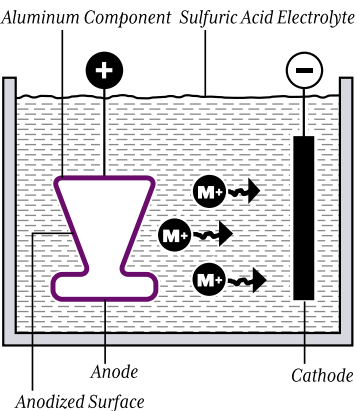
The Environment The usual problems with disposal of chemical waste have to be faced, but otherwise the process is non-toxic.

Competing Processes Electro-plating, vapor metalizing.



Attributes of Electro-less Plating

Surface hardness, Vickers	600–1100
Coating thickness, μm	20–120
Curved surface coverage	Very good
Processing temp., C	20–50



Anodizing

What Is It? Aluminum is a reactive metal, yet in everyday objects it does not corrode or discolor. That is because a thin oxide film $\text{-Al}_2\text{O}_3\text{-}$ forms spontaneously on its surface, and this film, though invisible, is highly protective. The film can be thickened and its structure controlled by anodizing. The process is electrolytic; the electrolyte, typically, is dilute (15%) sulfuric acid. The object to be anodized is made the anode (+) of the bath, with a potential difference of a few volts between it and the inert cathode. This sets up an enormous potential gradient across the oxide film, causing it to grow in thickness. The thicker film gives greater protection, and can be colored or patterned.

Functions Color, reflectivity; protection against corrosion and wear.

Design Notes Anodizing is most generally applied to aluminum, but magnesium, titanium, zirconium, and zinc can all be treated in this way. The oxide formed by anodizing is hard, abrasion resistant, and resists corrosion well. The oxide is micro-porous, allowing it to absorb dyes, giving metallic reflectivity with an attractive metallic, colored sheen; and it can be patterned.

Technical Notes There are three main types of electrolytes: “Weak dissolving” baths are based on boric acid; they form a thin (0.1–1 micron), non-porous oxide layer. “Medium dissolving” baths are based on a solution of chromic acid 3–10%, sulfuric acid 20%; oxalic acid 5%. They give a two-layer oxide: a thin, non-porous initial barrier layer with a porous layer on top of it. “Strong dissolving” baths contain phosphoric acid based electrolytes. The ability of the film to accept dyes depends on alloy composition: pure aluminum and Al-5 Mg alloys are well suited.

The Economics Equipment costs are moderately high, but tooling costs are low. Alternative treatments are chromating and phosphating; the ranked costs are: anodizing > chromating > phosphating.

Typical Products Anodizing is routinely used to protect and color aluminum; barrier layer anodic films on aluminum, titanium, or tantalum are the basis of thin-film resistor and capacitor components for the electronic industry; the anodic film is exploited in the printing industry for photo-lithographic printing plates.

The Environment The chemicals involved here are aggressive but manageable. Disposal of spent anodizing fluids requires a recycling loop.

Competing Processes Solvent- and water-based painting; electro-plating; electro-less plating; vapor metalization; chemical polishing; electro-polishing.

Attributes of Anodizing

Surface hardness, Vickers	600–1000
Coating thickness, μm	1–500
Curved surface coverage	Good
Processing temp., C	0–40



Mechanical Polishing

What Is It? “Spit and polish” is a metaphor for hard work, and one that is relevant here. Mechanical polishing is slow and expensive, and should be used only when absolutely necessary. There are many variants, among them: lapping, honing, and polishing. All make use of a fine abrasive, suspended in wax, oil, or some other fluid, that is rubbed against the surface to be polished by a polishing disk, a belt, or a shaped former.

Functions Color, reflectivity, texture; wear resistance; reduced friction; improved fatigue resistance.

Design Notes Almost any metal or ceramic can be polished using suitable tools and techniques. Polishing is usually applied to conical, cylindrical, flat, or spherical surfaces, but the parabolic surface of large mirrors is also polished. There are other ways of polishing – electro-polishing, chemical polishing – that give a highly reflective surface, but if precision is essential, as it is in accurate optical systems or in precision machine components, then mechanical polishing is the only choice.

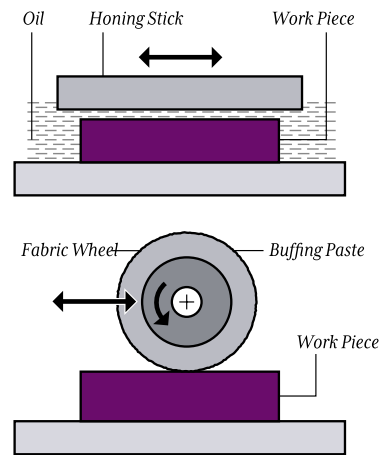
Technical Notes Polishing uses rotating wheels or belts and abrasives with or without lubricants. Less material is removed than with grinding and it produces a smoother surface. Polishing can be divided into four steps: roughening, greasing, buffing, color buffing. From the roughing step to the coloring step finer and softer abrasives are used and the pressure is reduced. The polishing compound can be in the form of a solid bar or liquid. While solid compounds are used in manual operations, liquid compounds are best when used on automatic machines: production time is reduced, as no time is needed to change the bars or sticks.

The Economics The equipment and tooling cost for manual polishing are low (capital cost \$100–\$1000; tooling cost \$10–\$200) but the production rate is low. Those for automatic polishing are greater (capital cost \$20,000–\$1,000,000, tooling \$1000–\$10,000) but with a higher production rate. Mechanical polishing is expensive; overspecification should be avoided.

Typical Products Pistons, pins, gears, shafts, rivets, valves and pipe fittings, lenses and mirrors for precision optical equipment (ground and polished to a precision of better than 0.1 micron).

The Environment Hazards depend on the specific operation, the component, its surface coating, and type of abrasive system in use.

Competing Processes Electro-polishing; chemical polishing.



Attributes of Mechanical Polishing

Surface hardness, Vickers	Same as Substrate
Coating thickness	Not relevant
Curved surface coverage	Poor
Processing temp., C	0–30

Electro-Polishing

What Is It? Electro-polishing is electro-plating in reverse. It offers an escape from the high cost of mechanical polishing, but at the penalty of much lower precision. The component is connected to the positive side of a low voltage direct current power source while a cathode is connected to the negative side, both immersed in a conductive solution. During the process, a layer of oxides or salts forms on the surface of the component; the layer controls the dissolution so that high points of a rough surface are dissolved faster than lower points. The final result is a metal surface with a smooth glossy appearance.

Functions Color, reflectivity, texture.

Design Notes Most metals can be electro-polished. Electro-polished surfaces are brilliant and have superior heat and light reflectance. The surface, however, has less mirror-like reflectivity than conventionally polished surfaces. More complex shapes can be polished than are possible by mechanical polishing, but less polishing occurs in holes, recesses, and slots than on more prominent surfaces.

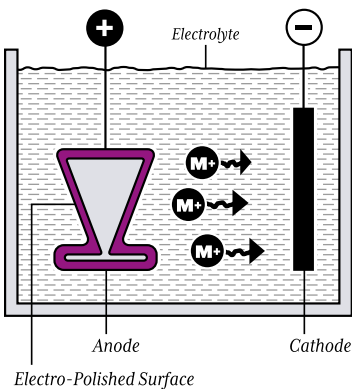
Technical Notes Electro-polishing is suitable for stainless steels, mild steels, and low alloy steels, aluminum, brass, zinc die-casting alloys, beryllium copper, nickel silver, molybdenum, and tungsten. No special pre- or post-treatments are needed. The most economical surface finish attainable by the process is 0.4 microns; 0.05 microns can be achieved – but at a higher cost.

The Economics The process does not normally require any special tooling, and so is economical for all levels of production. It requires less labor and less expensive equipment than mechanical polishing, but the initial capital cost can be high. Process time for any one component ranges from 3 to 10 minutes plus the time required for cleaning, rinsing, and other preliminary and subsequent steps.

Typical Products Used for components as small as 20 mm² in area: miniature electrical contacts, rivets, screws; also used for components as large as 1 m²: large metal panels.

The Environment Many electro-polishing baths pose environmental and health hazards. Some contain disagreeable chemicals – those with cyanogens require particular care. Protection from chemical pollutants and toxic vapor requires special precautions, as does the disposal of the polishing medium.

Competing Processes Mechanical polishing; chemical polishing; electro-plating; electro-less plating; vapor metalizing.



Attributes of Electro-polishing

Surface hardness, Vickers	Same as substrate
Coating thickness	Not relevant
Curved surface coverage	Average
Processing temp., C	0-90

Chemical Polishing

What Is It? If a bar of soap with a rough surface is immersed in water, it emerges smoother than it went in. That is because the soap dissolves faster at the peaks of the roughness than at the troughs because the local concentration gradient is steeper there. Chemical polishing relies on a similar principle. It is a process whereby a surface is smoothed by controlled chemical dissolution in a bath of acid containing additives that, by creating a surface boundary-layer, cause protrusions to dissolve faster than flat or intruded parts of the surface – there is no external power supply. The process is normally carried out at high temperatures to increase the polishing rate. Chemical polishing, like electro-polishing, is a way of brightening a surface, enhancing reflectivity, but without the dimensional precision of mechanical polishing. Much cheaper, of course.

Functions Color, reflectivity; texture.

Design Notes Chemical polishing offers great freedom in polishing items with blind holes and other recessed areas. It can treat components of different shapes at the same time. The reflectivity of the surface is less than that given by electro-polishing; the chemically polished surface is often anodized subsequently to produce a clear, colorless protective oxide coating.

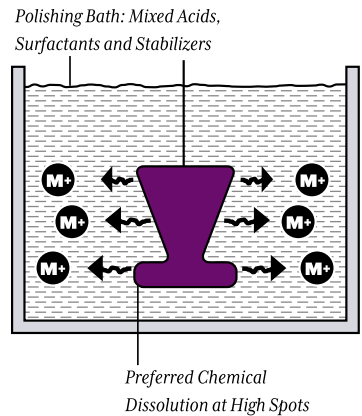
Technical Notes Aluminum, copper, and stainless steel are commonly treated by chemical polishing. Chemical polishing baths are generally based on combinations of phosphoric acid, nitric acid, sulfuric acid, hydrochloric acid, organic acids, and special surfactants and stabilizers; some are based on peroxides. The process is controlled by the chemistry of the bath, the temperature, and the time of immersion.

The Economics Chemical polishing has tended to replace electro-polishing due to lower costs. The process is cheap to set up and operate: no power supply or expensive racking are needed, and the capital investment and labor costs are low.

Typical Products Jewelry, razor parts, automotive trim, fountain pens, searchlight reflectors, architectural trim, household appliances, thermal reflectors for components of space vehicles.

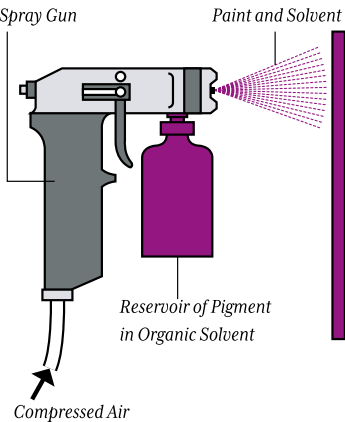
The Environment The chemicals involved here are aggressive but manageable. Disposal of spent chemical polishing fluids requires a recycling loop.

Competing Processes Mechanical polishing; electro-polishing; vapor metalizing; electro-plating; electro-less plating.



Attributes of Chemical polishing

Surface hardness, Vickers	Depends on substrate
Coating thickness	Not relevant
Curved surface coverage	Good
Processing temp., C	55–140



Attributes of Solvent-based Painting

Surface hardness, Vickers	10–16
Coating thickness, μm	10–1000
Curved surface coverage	Good
Processing temp., C	10–100

Coating

Solvent-Based Painting

What Is It? Watching paint dry is a synonym for boredom. But modern paints are far from boring. In solvent-based painting, coloring materials (pigments) are suspended, together with binding agents (resins), in a volatile organic solvent (VOC). When spread thin over a surface, the solvent evaporates; the resins hold the pigments in place to form a decorative and protective coating. Some few paints are not much more than this today. New developments now give formulations that dry in seconds, have fade-resistant colors, soft textures, visual effects, powerful protective qualities, and much more. But – and here it comes – there is a problem. Solvent-based paints are environmentally bad, so bad that their very future is under threat.

Functions Color, texture, feel; protection against corrosion and bacteria; wear protection.

Design Notes Solvent-based paints give the smoothest, most uniform coating and the greatest control of color – the automobile industry and most product designers insist on them. Metallic paints mix flake aluminum powder in the coating; the trick is to have the coating thin enough that the metal flakes lie in a plane so that the color does not “flip” when viewed from different angles. Color is determined by the differential absorption and reflection of the various wavelengths of light; the color seen is that at the least absorbed wavelength from the angle of view.

Technical Notes Paints are applied by brushing, dipping, or spraying, and can be applied to virtually any surface provided it is sufficiently clean.

The Economics Painting is cost-effective. The equipment costs are low for non-automated painting, but can be high if the equipment is automated. Paints are a \$75 billion per year industry.

Typical Products About half of all paints are used for decorating and protecting buildings, the other half for manufactured products, most particularly cars and domestic appliances; marine applications create important market for high performance corrosion and anti fouling formulations; “printers inks” are paints that play a central role in publishing and packaging.

The Environment Emissions from the evaporating solvents from solvent-based paints (VOCs) are toxic, react in sunlight to form smog, and are generally hostile to the environment. Auto manufacturers and others are under increasing pressure to meet demanding environmental standards. The solvents must now be recaptured, burnt, or recycled. There is growing incentive to replace them by water-based paints (but they dry slowly) or dry polymer coatings (but they cannot yet offer the same surface quality).

Competing Processes Water-based painting; powder coating; electro-painting.

Water-Based Painting

What Is It? Water-based (or latex) paints are synthetic resins and pigments, plus coalescing agents, that are kept dispersed in water by surfactants. They dry by evaporation of the water; the coalescing agents cause the particles of resin to fuse together (coalesce) as the water evaporates to form a continuous coating.

Functions Color, texture, feel; protection against corrosion, fungal and bacterial attack; wear protection.

Design Notes Water-based paints are based on acrylic, urethane, polyvinyl acetate (PVA), or epoxy dispersions. Acrylic emulsions are used in exterior applications where their non yellowing characteristics, as well as excellent weatherability, are outstanding. Water-based urethanes are suited to uses where good flexibility and toughness are important, such as leather and polymer coatings, but their major drawback is their high cost. PVA and epoxies give good weathering resistance. Water-based paints take longer to dry than many organic solvent-based paints, and give a surface finish that is less good.

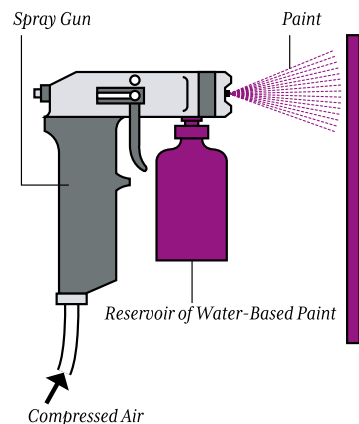
Technical Notes Water-based paints must be protected from freezing and applied at a minimum temperature of 10 C. Humidity and temperature control are critical for the drying time. A heat cure is sometimes necessary. Pigments must be compatible with water. Metallic particles are usually coated before being mixed into the paint to prevent chemical reaction with water. Many conventional binders (alkyls, acrylics, and epoxies) can be made water soluble by chemically attaching polar groups such as carboxyl, hydroxyl, and amide. Dispersions are very small particles of binders, less than 0.1 microns diameter, dispersed in water. Emulsions, or latex, differ from dispersions by having much larger particle size, on the order of 0.1 micron or more. They are made by precipitation in water and therefore do not need to be dispersed mechanically.

The Economics Solvent-based paint systems can usually be converted to water-based paint systems with a limited capital investment. The cost of water-based paints depends on the type; they can be less expensive than the solvent-based equivalent.

Typical Products Flooring, wood lacquers, decorative paints, automotive coatings, polymer coatings, inks, adhesives.

The Environment Water-based paints reduce VOC emissions and worker exposure to toxic pollutants and present no fire hazard. They are displacing solvent-based paints, although these dry fast and give a better surface finish with better adhesion.

Competing Processes Solvent-based painting; powder coating; electro-painting.

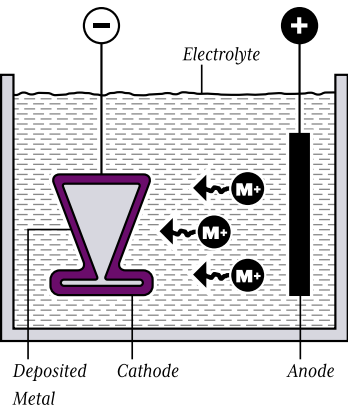


Attributes of Water-based Painting

Surface hardness, Vickers	10-16
Coating thickness, μm	10-1000
Curved surface coverage	Good
Processing temp., C	10-100



Electro-Painting



Attributes of Electro-painting

Surface hardness, Vickers	5-15
Coating thickness, μm	10-30
Curved surface coverage	Good
Processing temp., C	25-230

What Is It? In electro-painting the component forms the cathode in an electrolytic cell. The anode is inert – usually graphite or stainless steel – and the electrolyte is an aqueous solution in which the pigment is emulsified. An alkaline environment builds up at the cathode, causing the lacquer to coagulate. The charged particles of pigment are dragged by the electric field onto the surface of the component where they form a strongly bonded film. The film is relatively thin (10–30 microns), but gives good corrosion resistance, particularly if baked at 150–230 C after deposition. Other layers of paint are applied on top. The principle can be compared with electro-plating and is widely used in the automobile industry.

Functions Color; reflectivity; corrosion resistance.

Design Notes The process is largely used to give uniform undercoats on large, complex components. It lends itself to large volume production of products coated with the same color; examples are the electro-painting of a white paint on metal window and door frames and undercoating of auto body shells. The paint layer is distributed evenly over the surface, even in those areas that would otherwise be inaccessible. The main disadvantage is the requirement of a single, uniform color.

Technical Notes Electro-paint films are deposited from a dip tank. The bath consists of resin concentrate and pigment concentrate mixed with de-ionized water and small amounts of solubilizers and de-foamers. The concentration of non-volatile solids in the bath varies from about 10 to 20%, depending on type and composition. This process sometimes uses autophoretic paints; these are water-reducible paints deposited on metal surfaces by the catalytic action of the metal on the paint materials in the bath. Currently, only ferrous alloys activate the electro-paints available commercially. Tubular automotive frames are coated by this method, because the entire length of the tubing can be coated inside and out with equal ease.

The Economics The tooling costs are low; the capital cost medium.

Typical Products Undercoats for body lacquering of car bodies, single-color coatings for appliances, architectural panels and frames.

The Environment The process poses no particular environmental hazards, apart from the disposal of spent bath fluids.

Competing Processes Solvent- and water-based painting; powder coating.

Powder Coating

What Is It? Dust particles stick to the face of a television set because of a difference in electrical charge between the dust and the screen. This effect is used for practical purposes in electrostatic powder coating. It is an efficient, widely used process for applying decorative and protective finishes to metallic or conducting components. The powder is a mixture of finely ground pigment and resin that is sprayed through a negatively charged nozzle onto a surface to be coated. The charged powder particles adhere to the surface of the electrically grounded component. The charge difference attracts the powder to the component at places where the powder layer (which is insulating) is thinnest, building up a uniform layer and minimizing powder loss. The component is subsequently heated to fuse the layer into a smooth coating in a curing oven. The result is a uniform, durable coating of high quality, and attractive finish. In polymer flame coating, a thermoplastic in powder form (80–200 μm) is fed from a hopper into a gas-air flame that melts the powder and propels it onto the surface to be coated. The process is versatile, can be mechanized or operated manually, and can build up coatings as thick as 1 mm. A wide range of thermoplastic powders can be used and the process is cheap. The disadvantages: line-of-sight deposition, and surface finish that is inferior to other processes.

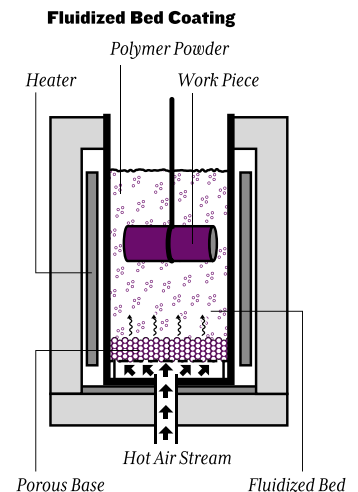
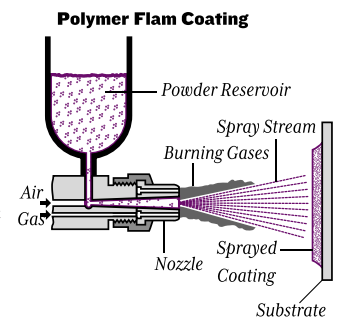
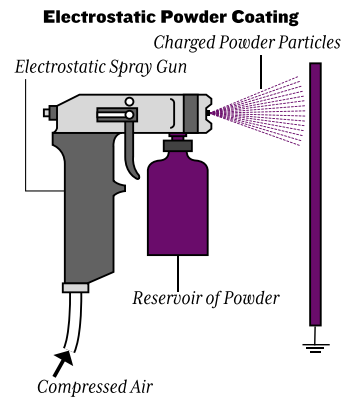
A hot donut, dunked into fine sugar, emerges with a crisp sweet skin. Fluidized-bed coating works in much the same way. The component, heated to 200–400 C, is immersed for 1 to 10 seconds in a tank containing coating powder, fluidized by a stream of air. The hot component melts the particles, which adhere to it, forming a thick coating with excellent adhesion. In electrostatic bed coating the bed is similar but the air stream is electrically charged as it enters the bed. The ionized air charges the particles as they move upward, forming a cloud of charged particles. The grounded component is covered by the charged particles as it enters the chamber. No pre-heating of the component is required but a subsequent hot curing is necessary. The process is particularly suitable for coating small objects with simple geometries.

Functions Color, texture, feel; protection against aqueous and organic corrosion; wear protection.

Design Notes Powder coating applications are limited to those that will sustain the processing temperatures required for polymer melting, curing, and film formation – but that includes all metals. The process can be easily automated, and can create thin films (50 μm), with good edge cover. Thick films can be applied in a single application, and the coating toughness is generally better than its liquid-based counterparts. Powder coatings are available in a wide variety of glosses and textures.

Technical Notes Electrostatic powder coating is routinely applied to components of steel, aluminum, magnesium, brass, copper, cast iron, and most metallic alloys. It can be applied to non-metals if their surface is first made conducting. The development of powder that can be cured at lower temperatures has allowed powder coating to be applied to non-metal surfaces such as ceramics, wood, and polymers. Coating materials are typically nylons, polyesters, polyethylene, polypropylene, polyvinyl-chloride (PVC), polyvinylidene fluoride (PVDF), and ethylene acrylic acid (EAA) co-polymers.

Almost all metals, ceramic, and even wood can be coated by polymer flame spraying – unlike electrostatic powder coating, it is not necessary for the surface to be conducting. Typical coatings are low and high density polyethylene, polypropylene, thermoplastic poly esters, and polyamides (Nylon 11). Pre-heating of the surface to 150–250 C may be necessary.



Attributes of Powder Coating

Surface hardness, Vickers	10–16
Coating thickness, μm	50–2000
Curved surface coverage	Good
Processing temp., C	125–400

Powder Coating, Continued

Fluidized-bed coating works well with nylons, PVC, acrylics, polyethylene, polypropylene, silicones, EVA, and polystyrene. The process gives good coverage, particularly of irregular shapes, allowing simultaneous coating of external and internal surfaces. Thick coatings are possible in a short time, with little waste of powder.

The Economics Powder coating is the fastest-growing finishing technique, now representing over 10% of all industrial finishing. For electrostatic polymer coating, the capital cost is medium, the tooling cost is low, and the equipment is not portable – a workshop process. The coating rate is between 5 and 20 $\mu\text{m}/\text{sec}$. For polymer flame spraying, the capital cost is low, the tooling cost is low, and the equipment is portable. There is no limit on the size of component. The coating rate is between 10 and 30 $\mu\text{m}/\text{sec}$. For fluidized-bed coating, the capital cost is higher than that for polymer flame spraying; the tooling costs are low. The coating rate is between 20 and 50 $\mu\text{m}/\text{sec}$.

Typical Products Automotive industry: wheels, bumpers, hubcaps, door handles, decorative trim and accent parts, truck beds, radiators, filters, numerous engine parts. Appliances: front and side panels of ranges and refrigerators, washer tops and lids, dryer drums, air-conditioner cabinets, water heaters, dishwasher racks, cavities of microwave ovens; powder coating has replaced porcelain enamel on many washer and dryer parts. Architecture: frames for windows and doors and modular furniture. Consumer products: lighting fixtures, antennas, electrical components, golf clubs, ski poles and bindings, bicycles, computer cabinets, mechanical pencils and pens.

The Environment The process uses no solvents and releases almost no volatile organic compounds (VOCs), so operators are not exposed to high levels of toxicity. Air pollution, fire hazards, and volatile organic compounds are low. Excess or oversprayed powders are recycled, blended, and re-sprayed with virgin material, which increases utilization up to 99% by weight.

Competing Processes Anodizing, organic and water-based painting.

Enameling

What Is It? Enameling is painting with glass. It creates coatings of exceptional durability: the enameled death-masks of the Pharaohs of Egypt look as bright, vibrant, and perfect today as they did when they were created over 3000 years ago (Tutankhamen, BC 1358-1340). A thin layer of glass powder with binder and coloring agent is applied to the object to be enameled by painting, spraying, or screen printing; the layer is then fused to the object, generally made of cast iron, pressed steel, copper, silver, or even – in the case of Tutankhamen – of gold, creating a continuous, strongly-bonded coating of colored glass. It is a hot process – the object being enameled must be heated to the melting temperature of the glass powder, limiting it to use on metals and ceramics.

Functions Color, texture, reflectivity; corrosion resistance; scratch resistance.

Design Notes Enamel coatings have exceptional hardness, wear and corrosion resistance, and can be made in an unlimited range of colors.

Technical Notes The glass used for enameling must flow easily, wet and bond to the metal surface, and have an expansion coefficient that differs only slightly from that of the underlying metal. This is achieved by using a glass rich in boric oxide (up to 35%), which also gives strong bonds and lustrous colors. In practice enameling usually marries two different kinds of glass: the base coat includes cobalt and nickel oxides, which help to form a strong bond with the metal; the second coat carries color and decoration. The result is extremely durable coating that is able to withstand thermal shock.

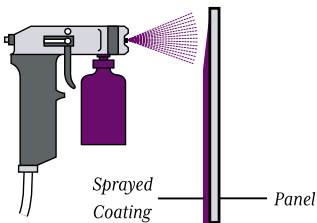
The Economics Enameling is not cheap – it is both slow and energy intensive. Its choice relies on the balance between quality and cost – its durability and aesthetic qualities are unequalled.

Typical Products In the home: baths, washing machines, dishwashers, heaters, stovetops, fireplaces, gas and electric cookers, clock faces, and cookware. In places you can't see: hot water services, storage tanks, car exhaust systems, printed circuits, and heat exchangers. In places you can see: street signs, railway signs, and murals. In the building industry: interior and exterior architectural panels, fascias, spandrels, and partitions.

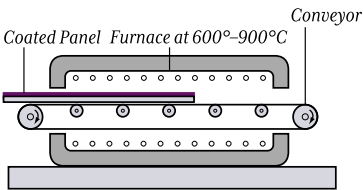
The Environment The process requires high temperatures, but is otherwise environmentally benign. Enameled surfaces are easily cleaned (even graffiti can be removed without damage), scratch resistant, and exceptionally hygienic.

Competing Processes Solvent- and water-based painting; powder coatings – though none give coatings of comparable hardness and durability.

Spray Coat



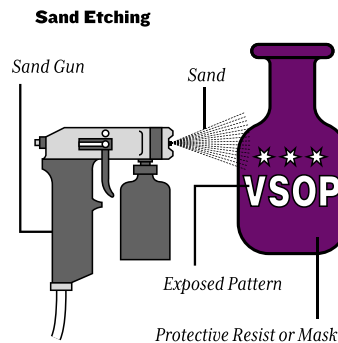
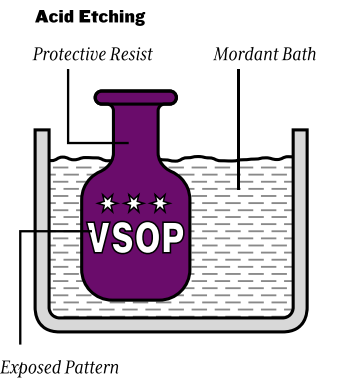
Fuse and Bond



Attributes of Enameling

Surface hardness, Vickers	7K-10K
Coating thickness, μm	500-1000
Curved surface coverage	Good
Processing temp., C	600-900

Etching



Attributes of Etching

Surface hardness, Vickers	7K-10K
Coating thickness, μm	500-1000
Curved surface coverage	Depends on process
Processing temp., C	18-60

What Is It? There are three basic processes for etching. Chemical etching is widely used to decorate glass, metal, and polymer objects. The areas or patterns to be etched are exposed to an acid or “mordant”; the areas that are not to be etched are protected with a wax resist. Glass used to be etched by hydrofluoric acid, a particularly nasty chemical that gives off poisonous fumes; today this has largely been replaced by proprietary etch-gels, by sand etching, or by engraving with a diamond tool. Copper, zinc, nickel, and steel are etched in various combinations of sulfuric, nitric, and hydrochloric acids.

Sand etching makes use of a jet of angular sand particles in a pressurized gas stream to erode the surface where it is not protected by a mask. The method works well with metals, ceramics, and polymers.

Electro-etching is a non-toxic way of etching of metals. Here the acid bath is replaced by one of copper sulfate (for etching copper) or zinc sulfate (for etching zinc) that never has to be changed. The object, protected by wax resists where necessary, is made the anode (+) of an electro-polishing bath, cutting into the areas of surface not protected by the resist.

Functions Color, texture, patterning, decorating.

Design Notes Etching is widely used to pattern glass and metal. The freedom of design is limited only by the technique for creating the wax pattern of resistance.

Technical Notes Techniques exist to etch glass, tile, wood, stone, metals, polymers. The acids used to chemical etching, are by their nature, particularly aggressive, requiring special containers, handling, and disposal. Sand etching is less demanding, but less controllable.

The Economics Chemical etching is slow and expensive. Sand etching and electro-etching are faster and cheaper.

Typical Products Decoration of glass, metal, polymer, or wood objects. Art: jewelry, ornaments, clocks, bookmarks, photographs etched into metal, medallions, street art, event posters, light switches. Advertising: plaques, business cards, graphic plates for brochures, awards, cover elements for annual reports, logos or tags to be placed on products, elevator button plates, signs to go on doors, name-plates, insignias, face plates, office decorations.

The Environment Chemical etching presents major environmental problems associated with toxic fumes, aggressive chemicals, and the difficulty of disposing of spent baths. Sand etching and electro-etching have none of these problems.

Competing Processes Texturing.

Texturing

What Is It? Texture can be created in many ways: by casting or molding in a patterned tool; or by rolling between patterned rolls ("diamond plate", used for stair treads, is made in this way). By crimping, pressing of sheet between patterned dies: pre-plated sheet, up to 0.8 mm thick, can be crimped to give sparkling reflective patterns; it is used, too, to increase bending stiffness and strength, allowing lighter gauge material for boxes and cans. By sand blasting, or abrasive polishing, the microscopic roughening of the surface in a random or patterned way (as in "brushed aluminum"). By laser texturing, usually applied to rolls or dies; the pulsed laser beam creates minute craters on the roll surface in a precisely controlled pattern that is then transferred to the component during the rolling operation. By electro-texturing, a process like electro-discharge machining (EDM), but using shaped graphite electrodes to smooth or give texture to the surface of the component. And by chemical engraving ("etching" and "chemical polishing") either of molds, rolls, and dies or of the component itself.

Functions Color, texture, feel; friction (grip).

Design Notes Texturing is important in design for both technical and aesthetic reasons.

It can improve product appearance, giving a visually interesting surface as well as hiding minor flaws, scratches, and sink marks. It can improve grip and it contributes to the tactile qualities of a product.

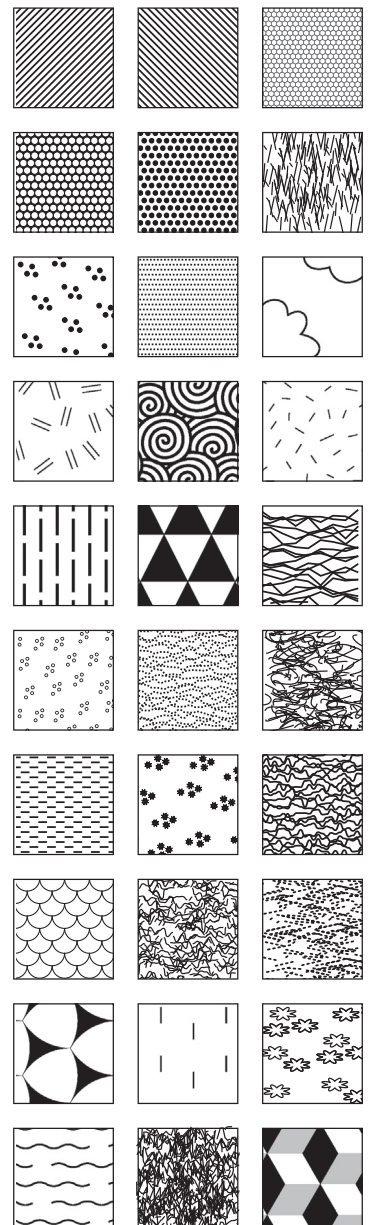
Technical Notes Virtually any material can be textured by one or another of the methods described above. Texturing by patterned rolls or crimping is limited to simple shapes (like sheet); electro-texturing, chemical engraving, and patterned tool methods allow greater freedom of shape.

The Economics The cost depends on the process. Some, like sand blasting and pattern rolling, are fast and cheap. Others, like laser texturing and chemical engraving, are slower, and consequently more expensive.

Typical Products There are two very broad classes of application: to impart visual features and to create tactile characteristics on a product.

The Environment Texturing processes do not present any particular environmental hazards.

Competing Processes Etching.



Attributes of Texturing

Surface hardness,
Vickers

Depends on
substrate

Coating thickness, μC

18-30

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