NATIONAL RESEARCH COUNCIL
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# BEYOND MAPPING

## MEETING NATIONAL NEEDS THROUGH ENHANCED GEOGRAPHIC INFORMATION SCIENCE

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Committee on Beyond Mapping:
The Challenges of New Technologies in the
Geographic Information Sciences

The Mapping Science Committee

Board on Earth Sciences and Resources
Division on Earth and Life Studies

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Barbara P. Buttenfield, University of Colorado, Boulder
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Joseph Wood, University of Southern Maine, Gorham

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Marc

Armstrong, University of Iowa, Iowa City. Appointed by the National Research Council, he was responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

We would like to thank David DiBiase for his white paper, "The U.S. Geospatial Education Infrastructure: Specifying, Developing, and Assuring Competence in the Geospatial Technology Workforce," which was submitted to the committee on June 5, 2005.

# Preface

Can you imagine formulating new methods and a coordinated training program for fighting forest fires while battling a raging forest fire? I can think of no better analogy to introduce this report. The mapping technologies that underlie this study are constantly and rapidly changing, and it is impossible for one person to keep abreast of all changes that are taking place. The playing field today is radically different from the playing field when this study was proposed in 2000. That the sponsoring agencies[1] requested such a study is not surprising, as each is, in its own way, in the middle of a forest fire in its own government department. They are to be commended for the wisdom to rise far enough above the conflagrations to realize that they needed advice and new directions.

Pulling together a group of dedicated individuals to attempt to answer the questions posed by the agencies was easy because of the current critical interest in the subject matter. But bringing together busy people, with their understanding of the part of the problem with which they were familiar, and asking for concurrence in a relatively short period of time and with few meetings, was about as easy as containing a forest fire when the wind constantly shifts directions and freshens and subsides at irregular intervals. The subcommittee held three meetings and a workshop

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[1] The Census Bureau, the Federal Geographic Data Committee, the National Geospatial-Intelligence Agency (formerly the National Imagery and Mapping Agency), the National Oceanic and Atmospheric Administration, the National Science Foundation, and the U.S. Geological Survey.

within a relatively short period of time yet was vividly aware that the nature of the field had changed rapidly between meetings, just as a forest fire is likely to change from hour to hour depending upon weather and human intervention.

Clearly North American industry and government took the lead in the rapid introduction of electronic technology into geographic information science. North American firms outstripped all competition in bringing useful software and world-leading hardware to the market. Government agencies saw these events unfolding and knew that the developments could help them perform their missions, but were unable to move as quickly as private industry. Government agencies at all levels (federal, state, and local) saw their roles transformed from serving as collectors and custodians of geographic information to becoming major users of geographic information, a not inconsequential change in a period as short as 10 years in some agencies. Academia was the slowest sector to respond, and the resulting lack of adequately trained people to meet industry and government needs has quickly mushroomed. The existing GIS/GIScience workforce, even given the increasingly powerful hardware and software it employs, cannot meet increased demands for geographic information.

In this report we try to summarize these changes during the past 30 years and to offer recommendations to quench some of the remaining hot spots in our forest fire. Although this report looks primarily to academia for long-term solutions, the challenge cannot be met by academia alone. New and innovative partnerships among industry, government, nonprofits, and academia will be required for success.

Thanks go to a group of dedicated individuals at the National Academies for preparing this report. I thank all of the original subcommittee members for their input at the meetings, which were both exciting and intellectually challenging, and for their written output after the meetings. Each member directed energies at one or more of the hot spots uncovered in the *Beyond Mapping* fire. Paul Cutler with the help of Kristen Campbell shepherded the subcommittee under the tutelage of Anthony de Souza. Left with many disjointed pages of rough draft from the subcommittee members, Ronald Abler, with input from Paul Cutler and Anthony de Souza, stepped forward to create a meaningful, yet still smoldering manuscript. After further review and helpful input from David Cowen and Caetie Ofiesh, Ron Abler was able to finally establish control over our forest fire. His efforts and those of the others mentioned above are greatly appreciated.

Joel L. Morrison
*Chair*

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# Summary

> *Digital mapping is about to change our world by documenting the real world, then integrating the information into our computers, phones, and lifestyles. Roll over, Mason and Dixon: spurred by space photography, global satellite positioning, mobile phones, search engines and new ways of marketing information for the World Wide Web, the ancient art of cartography is now on the cutting edge.*
>
> —Levy 2004, p.78

The announcement of the first Virtual Globes Scientific Users Conference[1] caps three decades of rapid technological change that has had profound and challenging impacts on the mapping sciences. Geographic information systems (GIS), the Global Positioning System (GPS), remote sensing, and other information technologies have all changed the nature of work in the mapping sciences and in the professions, industries, and institutions that depend on them for basic research and education. Today geographic information systems have become central to the ways thousands of government agencies, private companies, and not-for-profit organizations do business. Geographic information science (GIScience) is crucial to the way thousands of researchers perform science in numerous disciplines. The supply of GIS/GIScience professionals, however, has not kept pace with the demand generated by growing needs for more and improved geographic information systems and for more robust geographic data. In response to this dilemma, several government agencies[2] asked the National Academies to conduct a study that assessed the state of mapping sciences at the beginning of the twenty-first century (Sidebar S-1).

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[1] http://www.earthslot.org (accessed 24 May 2006).

[2] The Census Bureau, the Federal Geographic Data Committee, the National Geospatial-Intelligence Agency (formerly the National Imagery and Mapping Agency), the National Oceanic and Atmospheric Administration, the National Science Foundation, and the U.S. Geological Survey.

### SIDEBAR S-1
### Statement of Task

The study will assess the mapping sciences, addressing the following questions:

1. How have mapping/geographic information activities evolved and what have been their fundamental underpinnings?
2. What is the nature of the research agenda related to the mapping sciences and how might this agenda be addressed by current and possibly future collaborations among many disciplines?
3. What skills and knowledge will be required for professionals in the mapping sciences in corporations, agencies, and educational institutions?
4. What are the current strengths and weaknesses of the mapping sciences and how successful have they been in responding to technological change?
5. What is the state of the research infrastructure and the varying roles of universities, government laboratories, and the private sector?

A committee with expertise in geography, geography education, GIS, remote sensing, cartography, spatial analysis, geodetic science, cognitive science, survey engineering, civil engineering, environmental engineering, urban and regional affairs, environmental science, natural resource management, economics, urban economic geography, and computer science was formed to complete the study. The committee gathered, synthesized, and analyzed information from sponsors, personnel from government programs, representatives of industry, academia, and from professional societies and other nongovernmental organizations. The committee held three meetings and a workshop between June 2002 and February 2003. The workshop was organized to bring together technical visionaries as well as early adopters and innovators. As background material, the committee reviewed government documents and materials, pertinent National Research Council reports, and other relevant studies.

This report identifies the critical national needs for GIS/GIScience professionals. It examines the forces that drive and accompany the need for GIS/GIScience professionals, including technological change, demand for geographic information, and changes in organizations. It assesses education and research needs, including essential training and education, new curriculum challenges and responses, quality assurance in education and training, and organizational challenges. The report also looks at such GIS/

GIScience research needs as practical and theoretical challenges, society and infrastructure issues, and research agendas.

The focus for this report was developed during the study process. There was general agreement among the sponsors that the report would be most effective if it were to address university and college administrators because universities and colleges are the primary producers of GIS/GIScience professionals. It was also agreed that federal agencies and private organizations would find the report of interest because they are consumers of GIS/GIScience professionals.

The overriding challenge for society with respect to GIS/GIScience is to ensure that the next generation of scientists and technicians is produced in large numbers and is well prepared to build on the impressive progress achieved during the last 30 years. The committee offers five recommendations in response to that challenge:

1. The mapping sciences, despite numerous attempts to formulate one, still lack a coherent, comprehensive research agenda. Scientists from the multiple disciplines engaged in GIS/GIScience should make a concerted effort to achieve consensus on such an agenda, using the most recent outline proposed by the University Consortium for Geographic Information Science (UCGIS) as a point of departure.
2. Private-public funding models should be thoroughly investigated and, where feasible, should be applied to GIScience research in the United States. A possible model is Intelligent Transportation Systems and Services—Europe (http://www.ertico.com [accessed May 24, 2006]).
3. GIScience should be recognized as a coherent research specialty. The National Science Foundation should take responsibility for coordinating funding for GIS/GIScience, as recommended in Mark (1999).
4. Collaboration should be promoted among academic disciplines, private companies, and federal, state, and local government agencies to create a virtual network of GIScience researchers, laboratories, centers, and corporations. For example, an Institute for Geographic Information Science could be established under the joint auspices of the UCGIS (Sidebar S-2), representing major research universities, and the Open Geospatial Consortium (OGC), representing industry, government agencies and laboratories, and universities (Sidebar S-3).
5. The country's colleges and universities must become more flexible if they hope to keep pace with the GIS/GIScience industry and with government programs. Industry and government have taken the lead in developing and implementing digital approaches to map production; academic institutions follow as much as they lead. Accordingly:
    a. Academic institutions should reconsider their internal organization and reward structures to make them more responsive to emerging

### SIDEBAR S-2
### The University Consortium for Geographic Information Science (UCGIS)

The UCGIS is a nonprofit consortium of universities and other research institutions dedicated to advancing our understanding of geographic processes and spatial relationships through improved theory, methods, technology, and data.

The three major components of its mission are:

1. To serve as an effective, unified voice for the geographic information science research community;
2. To foster multidisciplinary research and education; and
3. To promote the informed and responsible use of geographic information science and geographic analysis for the benefit of society.

The goals of the UCGIS are:

- To unify effort by providing ongoing research priorities for advancing theory and methods in geographic information science and to assess the current and potential contributions of GIS to national scientific and public policy issues;
- To facilitate the expansion and strengthening of geographic information science education at all levels and to provide the organizational infrastructure to foster collaborative, interdisciplinary research in geographic information science; and
- To benefit society by promoting the ethical use of and access to geographic information and by fostering geographic information science and analysis in support of national needs.

SOURCE: UCGIS website, http://www.ucgis.org (accessed May 24, 2006).

specialties like GIS/GIScience, and to reward (or at least not penalize) faculty members who pioneer innovative topics and who engage in collaborative work with government agencies and private firms. Where credit for enrollments impedes cross- and multidisciplinary education, credit-sharing mechanisms should be employed. Devising institutional arrangements that favor robust GIS/GIScience and the funds necessary to sustain it will yield large dividends in the form of ready employment for undergraduates and advanced-degree graduates.

b. To meet the need for trained GIS/GIScience professionals as well as an informed citizenry, education programs in GIS/GIScience should

### SIDEBAR S-3
### The Open Geospatial Consortium

The Open Geospatial Consortium Inc. (OGC) is a nonprofit, international, voluntary consensus standards organization that is leading the development of standards for geospatial and location-based services. Through its member-driven consensus programs, OGC works with government, private industry, and academia to create open and extensible software application programming interfaces for geographic information systems and other mainstream technologies. Its mission is to lead the global development, promotion, and harmonization of open standards and architectures that enable the integration of geospatial data and services into user applications and advance the formation of related market opportunities.

SOURCE: OGC website, http://www.opengeospatial.org (accessed May 24, 2006).

be implemented at all levels of education (K-20, with special attention at K-16) in the United States. These programs should cut across traditional disciplinary borders and employ the latest technologies. The numerous ways GIS and GIScience can enhance spatial thinking (NRC, 2006a, pp.166-216) offer promising mechanisms for accomplishing that task, especially at the K-12 level. Maximum use should be made of the National Science Foundation’s programs for Research Experiences for Undergraduates (REU) and Research at Primarily Undergraduate Institutions (RUI) in pursuing this goal (NSF, 2006a,b).

c. The National Geospatial-Intelligence Agency and the National Science Foundation are to be commended for their recent programs encouraging needed research and organizational changes in academia. Such programs should be expanded and broadened to ensure that the country produces enough trained professionals to lead GIScience in the future.

d. More government-private, industry-academic partnerships are needed, and industry should consider funding relevant academic research and training to assure continued future innovation. The success of the National Center for Geographic Information and Analysis in obtaining private-sector funding for its work provides a model for such efforts and illustrates the benefits of academic-federal-industry coalition building. A government-industry-academic board should be established to promote such relationships, perhaps under the auspices of UCGIS and OGC or as part of the Institute for Geographic Information Science proposed in Recommendation 4. Industry and government could also expand their existing contributions to universities of serving on advisory boards, offering internships, and serving as adjunct faculty.

e. The UCGIS Model Curricula Body of Knowledge[3] should be maintained and widely adopted and implemented, since it provides a basis for determining the eligibility of education achievement claims for GIS certification.

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[3] http://www.ucgis.org/priorities/education/modelcurriculaproject.asp (accessed 24 May 2006).

# 1

# Geographic Information Science Today and Tomorrow

> *What makes* [Google Earth] *important is the trait it shares with other big steps forward in computing . . . it is not an end in itself, but a beginning of new opportunities for others, based on the new tools it provides.*
>
> —Fallows 2006, p. 140

A mere 30 years ago, stranded drivers could not place a cell phone call or push a button in their automobiles and have their precise locations almost instantly identified by a service that could dispatch assistance. Thirty years ago, the mobile telephones, pagers, and digital assistants that are now commonplace were little more than the dreams of visionaries, who were rarely taken seriously. Thirty years ago, scientists rarely used computers to visualize and analyze such complex geographic phenomena as the spread of a disease, trends in an evolving storm system, or variations in global soil moisture. Thirty years ago, geographic information systems were only beginning to be deployed in government agencies, the military services, police departments, private firms, and in higher education. Many of these changes were identified in a 1997 Mapping Science Committee workshop that assembled a group of experts from the private sector, academia, and government to focus on the future of spatial data in society (NRC, 1997). The resulting study described the changing organizational and technological environment in which all forms of spatial data are being created and used, and the related strategic questions facing organizations and stakeholders in the spatial data community. However, not even that group could predict the impact of the Internet, high-speed data access, cheap storage devices, and powerful search engines. Today numerous powerful and sophisticated mapping and visualization software is widely available at little or no cost to scholars, professionals, and ordinary citizens. Such utilities as Google Earth,[1]

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[1] http://earth.google.com (accessed 19 April 2006).

Virtual Earth,[2] World Wind,[3] EarthSLOT,[4] GeoFusion,[5] Placepedia,[6] and Flickr[7] provide a wealth of maps, images, and information that is cataloged and accessible by location.

The geospatial mapping technology trends that have accompanied these advances include, among others:[8]

- Migration from paper to digital storage and representation of data, allowing rapid spatial query and analysis;
- Shift from maps to mapping services (Mapquest, for example),[9] with inner workings and transactions often transparent to users, and from the mass production of multipurpose maps with long update intervals (the USGS 1:24,000 topographic map series, for example, or NOAA's Nautical Charts, the Rand McNally Road Atlas, Reader's Digest Atlases, or the National Geographic Society's maps) to customized, user-specified, on-demand maps for individual users;
- A broadening range of sensors and sensor locations, including those worn by people, animals, and robots, with improving capabilities for better spatial, temporal, and spectral resolution and with capacities for rapidly determining location using GPS;

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[2] http://local.live.com (accessed 19 April 2006). Microsoft's basic map utility.

[3] http://worldwind.arc.nasa.gov (accessed 19 April 2006). Permits users to zoom from satellite altitude into any place on Earth and view plan and 3-D versions of Landsat satellite imagery and Shuttle Radar Topography Mission data.

[4] http://www.earthslot.org (accessed 19 April 2006). A collection of 3-D GIS and terrain visualization applications designed to allow scientists, resource managers, educators, and the public to understand Earth and the Earth sciences. The site is maintained by the University of Alaska Fairbanks with support from the National Aeronautics and Space Administration and the National Science Foundation.

[5] http://www.geofusion.com (accessed 19 April 2006). A commercial visualization technology company that provides 3-D visualization of images of Earth. GeoFusion software is linked to that of the largest GIS software vendor.

[6] http://en.wikipedia.org/wiki/Placeopedia (accessed 19 April 2006), an online gazetteer that integrates Google Maps images (including satellite photos) and Wikipedia encyclopedia articles.

[7] http://www.flickr.com (accessed 19 April 2006). A photo-sharing website that can be accessed from Google Earth, thereby providing photos of specific sites organized by location.

[8] The evolution and fundamental underpinnings of GIS and GIScience requested in the *Beyond Mapping* Statement of Task question 1 constitute a fascinating tale that is told more fully in Appendix C. As this report itself evolved, and as its title suggests, its focus became dominated by the prospects that lie beyond the past and current mapping upon which it is based. Appendix C offers a more detailed account of evolution for those who desire it, but avoids diverting attention from current and future needs with a lengthy in-text history.

[9] http://company.mapquest.com (accessed 27 April 2006).

- Increased capability to instantaneously integrate multiple sources of geospatial information from geolibraries, clearinghouses, and data centers,[10] and;
- An increasingly rich array of ways to portray geospatial information in virtual reality and augmented reality.

Global positioning and navigation systems, hardware miniaturization, software innovations, wireless telecommunications, remote sensing, computer evolution, and the Internet have made such powerful software possible and fostered the penetration of geographic information systems into many realms of daily life. The utility of the increasing quantities of geographic information that has accompanied these technological changes has fostered rapid expansion in the use of geographic information systems (GIS). The resulting demand in the commercial, government, and private sectors for even more geographic data, for more advanced geographic information systems, and for personnel skilled in their applications has, in turn, fostered the development of geographic information science (GIScience), a vigorous and often ad hoc collaboration among many disciplines and professional specialties (Sidebar 1-1).

Today geographic information systems have become central to the ways thousands of government agencies, private companies, and not-for-profit organizations conduct business. Geographic information science is key to the ways thousands of researchers do science in numerous disciplines. For the most part, however, the supply of well-trained and well-educated GIS/GIScience professionals in the United States has not kept pace with the demand for more and improved geographic information systems and for more robust geographic data (Mondello et al., 2004). Although rapid growth in the GIS/GIScience labor force is forecast, without specific programs to accelerate that growth the United States runs the risk of losing its international lead in GIS/GIScience due to shortages of high quality GIS/GIScience personnel.

Meeting current and prospective demands for employees who will enhance the vigorous information-based economy of the United States presents many challenges, not least of which are those faced by colleges and universities. An information-based society demands new strategies for learning, practice, teaching, and research if the economic and social benefits it promises are to be realized. The United States remains the

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[10] Vast amounts of geospatial information can be downloaded from the Internet. For example, EOSDIS (the Earth Observing System Data and Information System) alone offers about at petabyte (1,000,000,000,000,000, or $10^{15}$ bytes) of data.

## SIDEBAR 1-1
## GIS and GIScience Definitions

A prominent geographic information system software vendor defines a GIS as

"a computer-based tool for mapping and analyzing feature events on Earth. GIS technology integrates common database operations, such as query and statistical analysis, with maps."[a]

The United States Fish and Wildlife Service, which uses geographic information systems extensively, defines GIS as

"an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information."[b]

The individual who coined the term GIScience defined it as

"a multidisciplinary research enterprise that addresses the nature of geographic information and the application of geospatial technologies to basic scientific questions" (Goodchild, 1992).

The definition adopted in the 2006 GIS/GIScience Body of Knowledge (DiBiase et al., 2006) is

"the science behind or underlying geographic information systems technologies and their applications."[c]

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[a] http://www.esri.com/library/brochures/pdfs/higher_ed_bro.pdf (accessed 4 May 2006).

[b] http://www.fws.gov/data/IMADS/glossary.htm (accessed 9 April 2006).

[c] http://www.ncgia.ucsb.edu/giscc/units/u002/u002.html (accessed 9 April 2006).

acknowledged leader in the development of GIS hardware and software, but individual and collaborative efforts on the part of educational institutions and employers will be needed if the country is to derive maximum benefit from its past investments in geographic information systems and geographic information science.

## NATIONAL NEEDS FOR GIS/GIScience PROFESSIONALS

> *A real barrier . . . is the lack of managerial leadership to oversee this entire process. We need GIS and GMS* [geographical management systems] *leaders.*
>
> —Wachter, 2005, p.12

Informed observers agree that the supply of competent GIS/GIScience professionals is inadequate to meet current and future needs of the geospatial enterprise. The National Aeronautics and Space Administration (NASA) launched a National Workforce Development Education and Training Initiative in 1997 to address the "serious shortfall of professionals and trained specialists who can utilize geospatial technologies in their jobs" (Gaudet et al., 2003, p.21). The largest GIS software vendor in the world estimated in 2000 that "the shortfall in producing individuals with an advanced level of GIS education was around 3,000 to 4,000 per year in the U.S. alone" (Phoenix, 2000, p.13). More recently respondents to a survey conducted by the American Society for Photogrammetry and Remote Sensing (ASPRS) noted a "shortage of trained workers emerging from educational programs," compounded by "the lack of the required skill sets among many of the graduates" (Mondello et al., 2004, p.13).

Moreover, a diversity of education and training approaches is needed to prepare practitioners in a wide range of fields to realize the potential of geospatial technologies (Longley et al., 2001). The U.S. Department of Labor (U.S. Department of Labor, n.d.) identified geospatial-related occupations as one of twelve high-growth employment sectors for the 2000-2010 period, with employment in those occupations projected to increase from 8 to 29 percent over the decade (Table 1-1). A 2004 article in *Nature* stated that

> earlier this year, the U.S. Department of Labor identified geotechnology as one of the three most important emerging and evolving fields, along with nanotechnology and biotechnology. Job opportunities are growing and diversifying as geospatial technologies prove their value in ever more areas (Gewin, 2004).

The size of the GIS/GIScience enterprise in the United States is difficult to estimate owing to its rapid evolution and to the absence of comprehensive, consistent occupational categories and data. One estimate reckoned that 175,000 workers were employed in the domestic remote sensing and geospatial information industries in 2004 (Mondello et al., 2004, p.11). In 2000, the GIS software vendor Environmental Systems Research Institute stated that some 500,000 individuals in the United States used GIS software at work, and that 50,000 were full-time GIS specialists (Phoenix,

**TABLE 1-1** Projected Growth in Geospatial-Related Occupations by U.S. Department of Labor 2000-2010

| Occupation | 2000-2010 Growth (projected percentage) |
|---|---|
| Cartographers and photogrammetrists | 18.5 |
| Surveyors | 8.1 |
| Surveying and mapping technicians | 25.3 |
| Architectural and civil drafters | 20.8 |
| Civil engineering technicians | 11.9 |
| Mechanical drafters | 15.4 |
| Electrical drafters | 23.3 |
| Electrical and electronic engineers | 10.8 |
| Mechanical engineering technicians | 13.9 |
| Industrial engineering technicians | 10.1 |
| Environmental engineering technicians | 29.1 |
| Geoscientists | 18.1 |

NOTE: Most industry insiders consider this conception of the "geospatial industry" to be far too inclusive (Seitzen, 2004). No one has questioned the projected growth of each of the listed components.

SOURCE: U.S. Department of Labor, n.d.

2000). Whatever the size of the GIS/GIScience labor force, it is not large enough; those using GIS continue to report that they are unable to find adequate numbers of qualified employees and GIS developers and vendors consistently lament shortages of capable geographic information scientists (Phoenix, 2000). Anecdotal evidence and informal reports from relevant scholarly and professional societies suggest that demand for faculty members qualified to teach GIScience in colleges and universities remains strong.[11]

## FORCES DRIVING THE NEED FOR GIS/GISCIENCE PROFESSIONALS

> *The combination of real-time and real-world mapping capabilities is extraordinarily powerful, leading to what I have termed Geographic Management*

---

[11] *Latitude*, an initiative of an organization called NITLE (National Institute for Technology and Liberal Education), promotes the use of mapping and GIS for the purposes of developing and enhancing a spatial understanding of liberal arts curricula. Among other strategies for achieving that goal, NITLE sponsors workshops at which college faculty and staff can learn about ways to incorporate GIS into their teaching (http://gis.nitle.org).

> *Systems [GMS]. . . . Today we have the potential to manage operations across space and over time on a minute-by-minute, second-by-second basis.*
>
> —Richardson 2005, p.5

Three elements of continued change will ensure and require a growing demand for GIS/GIScience professionals into the near future: (1) sustained and accelerating changes in information technologies, (2) expanding needs for more detailed geographic information, and (3) organizational change that responds to technological change and data availability.

## Technological Change

Basic capabilities for collecting, processing, analyzing, and disseminating geographic data continue to evolve on the foundation of the rapid progress made over the last 25 years. Airborne and satellite sensing devices are constantly being refined, and the resolution of readily available imagery continues to improve for almost all areas of Earth. Geographic data can now be collected from sensors that can be embedded in animals, buildings, vehicles, and even in millimeter-diameter "smart dust" (Hoffman, 2003). The number of mobile communication devices in service continues to increase, stimulating augmented demand for location-based services, at the same time that the capacities of the Internet, faster and lighter computers, and wireless access multiply to interconnect formerly distinct elements of information technology. The migration from paper to digital storage and representation of geographic data continues apace, as demand shifts from traditional maps and map vendors to map services that offer customized maps on demand for individual users. Simultaneously, lower entry costs have made it possible for many more organizations to engage in mapping in support of their operations or to produce products and services based on geographic information. Far from representing the end of a technological era, such services as Mapquest, Google Earth, and Geospatial One-Stop are but early way stations on a long journey of technological development (Sidebar 1-2).

These communication technologies have also made it possible for widely dispersed individuals to work on projects and provide services. Many companies are locating staff overseas to take advantage of lower wages and in response to domestic shortages of adequately trained personnel.

## Demand for Geographic Information

As the country and the world become increasingly interconnected, knowledge of place becomes ever more vital to a vast range of such hu-

### SIDEBAR 1-2
### Geospatial One-Stop

The Geospatial One-Stop Initiative is one of 24 e-government initiatives sponsored by the U.S. Office of Management and Budget (OMB) to enhance government efficiency, reduce costs, and achieve the goal of a more citizen-based and results-oriented government. To manage the initiative, an intergovernmental board of directors has been established that is composed of state, local, tribal, and federal representatives. This board provides guidance on the direction of the project and ensures dialogue among the levels of government making major investments in geospatial information. The project was initially to have a finite lifespan of two years but has been continued indefinitely. It is focused on the seven framework digital data themes in common use specified by the Federal Geographic Data Committee (FGDC). Participating data producers must classify and document their data holdings following accepted standards. Geospatial One-Stop's primary objectives are to:

- Develop and implement data standards for National Spatial Data Infrastructure (NSDI) framework data;
- Maintain an operational inventory of NSDI data and publish the metadata records in the NSDI Clearinghouse Network;
- Publish metadata for planned data acquisition and update activities;
- Develop and deploy prototypes for enhanced data access and Web mapping services for geospatial data; and
- Establish a comprehensive electronic portal as a logical extension to the NSDI Clearinghouse Network.

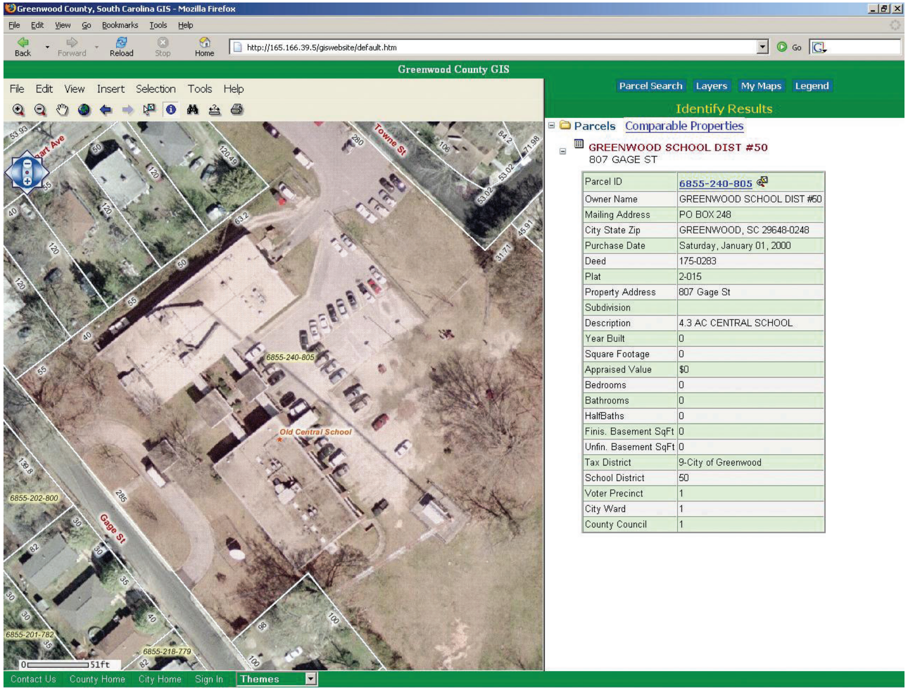
The initiative will build on investments already made in developing the NSDI and on advances in geospatial information technologies to encourage greater collaboration and coordination among federal, state, and local governments; tribal governments; the private sector; and academia.

SOURCE: http://www.geo-one-stop.gov (accessed 24 May 2006). NRC, 2003.

man activities as responses to emergency 911 calls, weather forecasting, air traffic control, crop monitoring, and national security. Humans rely constantly on place-based knowledge as they navigate, describe places to others, study the history of localities, or plan for the future of places where they live. As globalization causes events in distant places to induce changes in familiar localities through the outsourcing of formerly local jobs or the consequences of distant political upheavals, the demand for detailed geographic information grows, along with the need for more robust ways of storing, synthesizing, analyzing, and understanding the meaning of information about places (Friedman, 2005). A related force driving accelerated societal demands for geographic information and GIS/GIScience professionals is the increasing accessibility to that information. Today anyone with access to a computer or a Global Positioning System (GPS) receiver can make maps and publish them on the Internet, empowering individuals, local communities, and private firms to create or capture data in their own ways instead of relying on federal and state governments to produce it for them (NRC, 1997).

Access to geographic information received a huge boost with its recent incorporation into major commercial search engines such as Google. The enormous financial and technical resources that Google and other software companies command have changed the way average citizens can access geographic information—and even add their own content. Free, robust, and dynamic Web-based tools for accessing geographic information provide new ways for the public to search for all kinds of geographic information, including tourist sites, property tax assessments (Figure 1-1), and even the locations of convicted sex offenders (Figure 1-2). Maps and aerial photography have become part of the standard content for many commercial websites, and a rapidly increasing number of companies are developing new marketing strategies based on geographic search and visualization tools. The RE/MAX real estate company in Colorado, for example, has developed an application billed as "The Future of Real Estate." It uses Web-based search engines to select subsets of prospective properties from traditional multiple listing services and allow buyers to view property locations on high-resolution aerial photographs overlaid with information on schools and other services and amenities (Figure 1-3). Virtual tours of individual properties can be taken using other Internet tools.

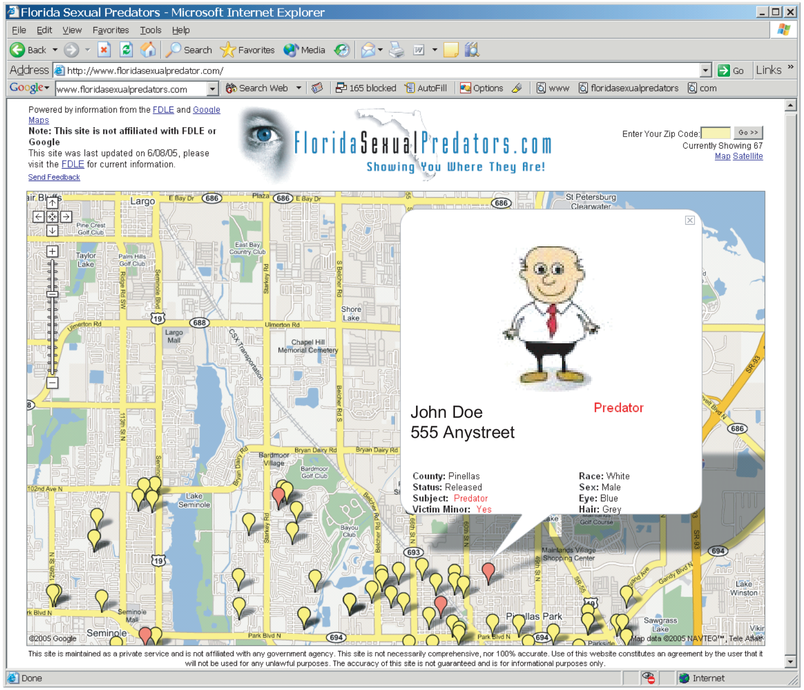
Like the demand for more geographic data, the demand for better data seems insatiable. For many applications, data currency is crucial, as in emergency 911 dispatching systems. Desirable data are accurate, detailed, as inexpensive as possible, and easy to find and retrieve. Data should be amenable to analysis, modeling, visualization, and use in decision support systems, and the tools needed for those functions should be as accessible as the data themselves. For government agencies, private entrepreneurs, and scholars, success relies on geospatial information being current, timely, accurate, cheap, easy to manipulate, and easy to retrieve. These are persistent desires, and they will continue to drive the further development of geographic information science in the future, just as they have in the past.



GREENWOOD SCHOOL DIST #50
807 GAGE ST

| | |
|---|---|
| Parcel ID | 6855-240-805 |
| Owner Name | GREENWOOD SCHOOL DIST #50 |
| Mailing Address | PO BOX 248 |
| City State Zip | GREENWOOD, SC 29648-0248 |
| Purchase Date | Saturday, January 01, 2000 |
| Deed | 175-0283 |
| Plat | 2-015 |
| Property Address | 807 Gage St |
| Subdivision | |
| Description | 4.3 AC CENTRAL SCHOOL |
| Year Built | 0 |
| Square Footage | 0 |
| Appraised Value | $0 |
| Bedrooms | 0 |
| Bathrooms | 0 |
| HalfBaths | 0 |
| Finis. Basement SqFt | 0 |
| Unfin. Basement SqFt | 0 |
| Tax District | 9-City of Greenwood |
| School District | 50 |
| Voter Precinct | 1 |
| City Ward | 1 |
| County Council | 1 |

**FIGURE 1-1** A Web-based GIS tool able to display property tax assessments. Many local governments have developed Web-based mapping systems that allow the public to view and retrieve information pertaining to specific tax parcels, as in the school shown here. While property ownership information has always been open to the public, the ability to access it in an interactive mapping environment provides a new perspective (http://165.166.39.5/giswebsite/default.htm [accessed 24 May 2006]). Used with permission.



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Currently Showing 67
Map Satellite

John Doe
555 Anystreet

Predator

**County:** Pinellas
**Status:** Released
**Subject:** Predator
**Victim Minor:** Yes

**Race:** White
**Sex:** Male
**Eye:** Blue
**Hair:** Grey

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**FIGURE 1-2** A Web-based GIS tool showing residences of sex offenders. The laws relating to public disclosure of the residence of sex offenders take on a different dimension when the addresses become part of a Web-based interactive mapping application (http://www.floridasexualpredator.com [accessed 24 May 2006]). This example listing has been made anonymous. Google Maps is a trademark of Google Inc. Used with permission.

**FIGURE 1-3** A Web-based GIS tool able to perform real estate searches. A commercial real estate company has coupled traditional Multiple Listing Service information with the mapping and visualization capabilities of Google Earth to provide a new way for users to perform real estate searches in Colorado (http://www.coloradofuture.com [accessed 24 May 2006]). Google Earth is a trademark of Google Inc. Used with permission.

## Changes in Organizations

Abundant geographic data and its uses have brought about changes within many organizations as well as in interactions among organizations. Transforming mapping from the art of a few to standard software functionality results in less centralized management, less control over geographic data, and fuller reliance on a distributed network of individuals and organizations for capturing and managing stores of geographic data (NRC, 1997). Organizations using GIS technologies now face the need to manage resources and technologies with which they have little experience. Another force for organizational change in GIS/GIScience is an increased focus on problems and questions that do not fit neatly within such traditional categories as the purview of an individual academic discipline, or the prerogatives of the private and public sectors. Effectively addressing global warming, the threat of influenza pandemics, or national security, for example, demands the knowledge and skills of professionals from a variety of sectors and specialties.

While many organizations produce digital geospatial data, few have the resources to produce all the data they require. This means that organizations are spending increasing amounts of time searching for data and negotiating or coordinating with other organizations to help meet their needs. These negotiations are taking place across all sectors (public, private, nonprofit, and academic) and are resulting in new forms of collaborations as well as new organizations. Some of the organizations most affected by technology and GISciences changes are the traditional national mapping organizations.

### *Federal*

The U.S. Geological Survey (USGS), with long-standing responsibilities for national mapping, has faced significant organizational challenges over the last decade in response to the evolution of the GISciences. The ability of many other entities to produce more current, higher-resolution data and to market data products effectively has forced USGS to reexamine its mission and roles and to consider new collaborations and partnerships (NRC, 2001, 2003b). The realities of declining budgets for mapping functions, a workforce lacking many of the necessary skills to respond to today's geographic data management requirements, and shifting mandates as the federal government tries to coordinate geospatial activities, have contributed to the need to reassess USGS operations, a challenge faced by similar mapping organizations worldwide.

The USGS response is the Center of Excellence in GIScience (CEGIS) established in January 2006 within the USGS Geospatial Information Office. CEGIS conducts, leads, and influences the research and innovative solutions required by the National Spatial Data Infrastructure (NSDI) and the emerging GeoSpatial Web. The mission of CEGIS is to:

- Provide leadership to identify, conduct, and collaborate on GIScience research issues of national importance;
- Provide timely, efficient, and intelligent access to new and archived USGS geographic data needed to conduct science and support policy decisions;
- Develop innovative methods of modeling and information synthesis, fusion, and visualization to improve our ability to explore geographic data and create new knowledge;
- Develop credible and accessible geographic research, tools, and methods to support decision making related to the human and environmental consequences of land change;
- Assess, influence, and recommend for implementation technological innovations for geospatial data and applications; and
- Maintain world-class expertise, leadership, and a body of knowledge in support of the NSDI.

CEGIS will consist of a cadre of government research scientists, largely located at the National Geospatial Technical Operations Center in Lakewood, Colorado. It will directly fund its staff and some specific research activities within the USGS. Other activities that support the CEGIS research agenda will be funded through a competitive research prospectus process. CEGIS staff will be augmented by postdoctoral researchers and by academic and industry scientists in visiting positions.

GIScience initially involved, and still includes, the science behind the traditional mapping disciplines of cartography, photogrammetry, remote sensing, and surveying. Today it also includes broader issues related to the modeling and representation of geographic data, phenomena, and processes; human cognition of geographic information; the analysis and description of uncertainty; spatial analysis and modeling, including GIS; scale; geographic ontologies;[12] visualization;[13] and similar topics.

Examples of specific questions of relevance to the Geospatial Information Office (GIO) are:

- What roles do scale, resolution, and uncertainty of scientific information play in addressing different types of issues?

---

[12] GIS representations of geographical phenomena and data.

[13] Rendering data into visual geospatial representations.

- How can science performed on the basis of natural boundaries support decisions that affect areas defined by administrative or social boundaries?
- What science-based tools and products can be developed to support decision making?
- How can data mining algorithms be designed to handle geospatial data, spatial data access structures, and use of domain knowledge for improved query processing and mining?
- Can a theoretical model be developed and verified that provides a basis for fusing geospatial datasets of different geometries, resolutions, and accuracies?
- Can such a model provide a basis for automatically combining data through access to metadata that includes resolution and accuracy?
- Can we develop appropriate methods of visualization to handle the generalization of features at different scales, deal with color and contrast issues when combining multiple raster and vector datasets, and represent and display critical data elements on a variety of display media?

While these topics generally represent long-term research areas, the GIO also seeks shorter-term opportunities to apply new understanding and capabilities gained from research in these areas to enhance the development and operation of the National Map (http://nationalmap.gov [accessed 24 May 2006]).

Research activities necessary to achieve the National Map vision include the development of methods necessary to derive and display seamless, generalized, consistent data and topographic maps from the best data available from a variety of distributed federal, state, county, and local government and private-sector sources. Extraction and long-term maintenance of feature information, including capabilities for individual feature identification and transactional update, Internet-based data collection and editing, metadata population and maintenance, and integration of open-source and proprietary systems and data also are research themes. Also included is the development of technologies to integrate laser- and microwave-based technologies, combined with airborne Global Positioning System capabilities, into the production of the National Map data.

CEGIS will also conduct, support, and collaborate in research to address critical geographic information science questions of importance to the USGS as a whole and to the broader geospatial community. As an outgrowth of and complement to this research program, the CEGIS will support and collaborate in technological innovations that further the implementation of the NSDI (Steven Guptil personal communication to David Cowen, April 5, 2006).

The Office of Management and Budget (OMB) recognized 15 years ago the need for agencies to cooperate in order to more effectively develop and maintain geospatial data (OMB, 1990). OMB created the Federal Geographic Data Committee (FGDC) to provide a forum for federal agencies and states—and more recently professional societies, local governments, and universities—to discuss geospatial data issues and to consider data standards (Sidebar 1-3).

### *Private*

Structural changes within private organizations in response to GIS/GIScience are likely to be self-initiating in response to market forces. An increasing number of firms recognize that ready access to detailed spatial information represents new market opportunities. Innovative companies are capitalizing on these opportunities. Private firms in forest management and real estate have long relied on robust GIS tools to inventory and manage their assets. Most utility companies now rely on detailed geographic information for all components of their infrastructure to feed the decision support systems they use to monitor their net-

### SIDEBAR 1-3
### The Federal Geographic Data Committee

The Federal Geographic Data Committee (FGDC) is an 18-member interagency committee that coordinates the development, use, sharing and dissemination of spatial data nationally. The Office of Management and Budget (OMB) established the committee in the 1990 revision of OMB Circular No. A-16 and reestablished it in the circular's 2002 revision (OMB, 1990, 2002). The FGDC evolved in part from a committee established by OMB in 1983 called the Federal Interagency Coordinating Committee on Digital Cartography (FICCDC). FGDC receives a budget of approximately $4.9 million from the USGS to facilitate coordination, develop standards, sponsor cooperative agreements, and support the FGDC secretariat. FGDC has developed and issued approximately 25 spatial data standards, including the metadata standard; established clearinghouses that provide access to spatial data using metadata standards; fostered hundreds of cooperative agreements that sponsor the development of framework data and the development and testing of spatial data access technology and interoperability; and disseminated numerous publications and educational materials describing the National Spatial Data Infrastructure (NSDI) and its various components.

SOURCE: FGDC, 2005; NRC, 2003a.

## SIDEBAR 1-4
## Job Posting for a GIS-related Position

GIS Analyst/Programmer

Miner & Miner has a career opportunity for a motivated person to join our application team. This person will have strong object-oriented programming skills and geographic information systems experience to work as a member of our project consulting team. This individual will perform a variety of tasks relating to implementing and customizing applications for electric, water, and gas utility companies. This individual will play a role in the development of new tools and the enhancement of existing software. This person will work closely with project managers, technical leads, and clients.

This position requires:

- Bachelor of science degree in computer science, engineering, or geography (or related field with computer emphasis). Relevant job experience will also be considered in lieu of a degree.
- At least two years experience with ArcGIS and other ESRI products. Experience with Smallworld or Intergraph will also be considered.
- At least one year of extensive work experience developing end-user applications with an object-oriented programming language, such as C# or Magik.
- Experience with commercial RDBMS [relational database management system], such as Oracle or SQL [structured query language] server. . . .

SOURCE: TechJobsCafe.com, 2005.

works. During an outage, sophisticated tools now enable utility companies to link customer phone numbers to precise nodes on a network and quickly pinpoint the location of the problem. Many companies now integrate their GIS departments with their standard information technologies. This mainstream enterprise view of information systems has led to demands for experts who can integrate geospatial information with other information technologies. Many such firms have major recruitment problems. Sidebar 1-4 shows a recent job advertisement that illustrates the type of skills that are in demand.

As new business opportunities emerge, they stimulate demand for current, high-resolution geographic data. The information that is used to dispatch emergency vehicles, calculate property taxes, and drive dashboard navigation systems can also be employed in site selection and market analysis. Consequently, an energetic market has developed for firms that capture, convert, and maintain geospatial data. One company reported that it had 15 vacancies and planned to hire another 35 people the following year (A. Miglarese, personal communication to D. Cowen, January 12, 2005). More important, the president of the company suggested that it was impossible to find people with the skills to integrate digital imagery with other information systems. The shortage is so acute that the Management Association for Private Photogrammetric Surveyors (MAPPS) is inviting its members to send human resources personnel to attend a workshop on ways to locate and recruit a skilled workforce.

In addition to the expanding business opportunities in marketing, real estate, tourism, and similar data-related enterprises, there are critical needs to be met on the tool development side of commercial enterprise among firms that can create commercial off-the-shelf (COTS) and customized computer software. While much of the effort of GIS software vendors over the past 25 years has focused on the development of tools to solve specific data capture and editing problems or to provide powerful analytical tools, demand is now growing for specialized Web-based applications. Firms specializing in Web-based GIS consistently report great difficulty in finding personnel who are expert in modern programming techniques, sophisticated database management, and geospatial information standards requirements (G. Ehler to D. Cowen, personal communication, April 17, 2006).

Private firms have offered training in their respective software products for many years, and many organizations, public, private, and nonprofit alike have sent staff for such training. Governments have also undertaken organizational initiatives, both within individual agencies at local, state, and national scales, and in creating intergovernmental organizations such as FGDC to coordinate their complementary and overlapping efforts.

### *Colleges and Universities*

Traditional university programs are not well structured to provide students with these kinds of qualifications. It is difficult for such traditional academic disciplines as forestry and business administration to add the additional coursework in GIScience that would provide graduates with the proficiency employers desire. In recognition of the need for an innovative approach, the University of Texas at Dallas initiated a new Ph.D. program in GIScience (Sidebar 1-5) that is jointly offered by its School of Social Sciences, School of Natural Sciences and Mathematics (specifically in the Department of Geosciences), and School of Engineer-

### SIDEBAR 1-5

### University of Texas at Dallas Doctoral Program in GeoSpatial Information Technology

The innovative structure of the University of Texas at Dallas doctoral program in geospatial information technology reflects geographic information science's origins at the confluence of work in multiple disciplines, including geography, computer science, engineering, geology, and various social, policy, and applied sciences.

Unlike programs at other schools in which geospatial information science is offered as a concentration within traditional geography, geology, environmental science, or engineering programs, the degree at UTD is devoted solely to GIScience, focusing on advancing the technology, associated theory, and enhancement of application in a variety of substantive realms. It provides a unique option for students wishing to concentrate in this inherently cross-disciplinary specialty.

Students educated in this manner will be attractive to the burgeoning geospatial technology industry, and to academia, because of their ability to build bridges to other disciplines. A critical mass of quality faculty have been assembled under this programmatic umbrella by bringing together faculty with expertise who are currently distributed among multiple departments across the UTD campus.

The program's architects expect that many students will enter the program with a bachelor's or master's degree (and/or work experience) in such applications as public administration, geology, or economics, or a technical specialization (engineering, computer science, statistics, etc.) with the intent of advancing existing practice with geospatial information sciences in that application or expanding the technological or theoretical base for geographic information science.

SOURCE: http://www.bruton.utdallas.edu/educ/gisphd.html. Accessed 19 April 2006.

ing and Computer Science. The program is devoted solely to GIScience, focusing on the advancement of the technology, associated theory, and enhancing applications to substantive problems.

It is interesting that Harvard University has recently chosen to begin the process of reestablishing a geography program by focusing on research and education in spatial analysis and geographic information. Working with entities across the university, the new Harvard Center for Geographic Analysis (CGA) will be responsible for strengthening university-wide geographic information systems infrastructure and services to enable scholarly research that would use, improve, or study geospatial analysis techniques. In creating the center, the university has also committed itself to raise funds for two senior positions that will provide strength in such fields as geospatial analysis, geoinfomatics, and geography. The CGA will enhance undergraduate and graduate curricula across the university and work with faculty in Harvard's Division of Engineering and Applied Sciences, Faculty of Arts and Sciences, Graduate School of Design, and the Harvard School of Public Health to develop and support appropriate courses, course modules, and laboratories (Graun, 2006).

Although commerce and industry lead the government and academic sectors in devising and applying new developments in GIS, the country's colleges and universities remain the primary source of new GIS/GIScience professionals. The ability of governments and the private sector to meet their respective missions is increasingly hampered by the shortage of qualified professionals. Society's needs for these professionals could be more effectively met if the traditional departmental structure of colleges and universities were more hospitable to such diverse emerging specialties as GIS/GIScience.

# 2

# Education and Curriculum Needs in GIS/GIScience

Geographic information systems (GIS) and geographic information science (GIScience) demand new skills and knowledge. Professionals trained in traditional curricula in such departments as geography, civil engineering, and computer science fail to develop insights into the critical linkages among these disciplines that are needed by today's GIScience professionals. Consequently, curricular and structural changes should be integral components of plans to produce the GIS/GIScience professionals who are in such short supply. Moreover, it may be desirable to take formal steps to ensure consistency and quality in their preparation. Education in new specialties cannot be separated from the research that underlies it, and as is true of any new intellectual enterprise, geographic information systems and geographic information science present new challenges across the pedagogical spectrum from applications to fundamental geographic and cartographic theory.

## GIS/GIScience TRAINING AND EDUCATION NEEDS

Maps play critical roles in any discipline that investigates phenomena dispersed over Earth's surface. Hence, anthropologists, ecologists, epidemiologists, foresters, geographers, geologists, meteorologists, and scientists in many other disciplines make extensive use of maps and engage in mapping. Anatomists, astronomers, genomicists, physiologists, and other scientists who use spatial perspectives also find maps invaluable in their work at scales less than or beyond those normally found in geographic mapping. Technology and the growing use of spatial analysis ensure continued rapid growth of mapping in the decades to come (Hall, 1992). Because maps are such essential tools, students should learn about them as part of their preparation as scientists, and many do in response to the growing value of GIS skills in the job market. With widespread adoption of GIS as a tool for environmental management, planning, and spatial decision support, GIS courses are now routinely offered as service courses on many campuses, and are increasingly required in programs in Earth science disciplines. Looking toward the future, informed citizens will need to use and understand the outputs of geographic information systems and the rudiments of geographic information science. How else will communities be able to make sound decisions about smart growth, environmental preservation, adequate water and sewage systems, and similar issues?

Across the spectrum of GIS/GIScience competence (Sidebar 2-1), ranging from public awareness at the most elementary level to geographic

## SIDEBAR 2-1
## Seven Levels of GIS Competence

Seven levels of GIS competence are, in ascending order:

1. Public awareness of GIS and its uses;
2. Basic spatial and computer understanding;
3. Routine use of basic GIS software;
4. Higher-level modeling applications of GIS;
5. Design and development of GIS applications;
6. Design of geographic information systems; and
7. GIS research and development.

Undergraduate degree programs should foster competence in all college and university graduates in the first two levels regardless of discipline owing to the pervasive use of GIS. Students interested in employment in agencies or firms that use GIS should be competent at level 3 in order to use commercial off-the-shelf software. Level 4 requires abilities in spatial analysis, computer programming, and database management. Competence in software engineering must be added to fulfill level 5 responsibilities. Level 6 workers must also acquire advanced analytical and technical skills, including systems analysis, database design and development, user interface design, and programming. Level 7 professionals are capable of leading research and development teams in government agencies, at software vendors, and in colleges and universities.

SOURCE: DiBiase et al., 2006; Marble, 1997.

information science research and development at the most advanced (the order does not necessarily imply hierarchy or progression), the number of professionals trained at levels 2-4 in the sidebar has expanded rapidly. The supply of graduates prepared to assume levels 5-7 responsibilities, however, continues to fall further behind the numbers needed (Marble, 1997).

While GIScience education was maturing, several concerns arose regarding its evolution:

1. Members of the GIScience community have questioned whether academic training provides the depth of understanding needed to serve the rapidly growing profession (Wikle, 1999).
2. Another concern has been achieving an appropriate balance between learning software and understanding the foundation concepts needed to use geographic information systems intelligently (Marble, 1997). There is widespread uneasiness about "button pushers who know cookbook applications but are unable to work through a problem from start to finish" (Gober et al., 1995, 1997, p.216). Some GIS courses are too focused on software at the expense of the critical concepts and habits of mind required for the effective practice of evolving mapping science.
3. GIScience coursework has crowded the already full course loads of university students. As a result, many graduates now take fewer courses in their majors and fewer courses (such as statistics) needed for workplace success.
4. The methods used to teach GIScience have not been sufficient to meet the growing need for mapping science professionals, and attention should be given to improving GIScience pedagogy (Paul, 2004).

In recent years, as GIS/GIScience organizations have worked to identify the important thrusts for research and standardization of the curriculum, there has been a proliferation of applicable books and journals. In fact, a search of Amazon.com found more than 2,503 entries for "geographic information systems." One of the most complete listings of GIS materials is maintained at the Virtual Campus Library of the Environmental Systems Research Institute (http://campus.esri.com/campus/library/bibliography/ [accessed 24 May 2006]), which provides a useful breakdown of the 147 books listed on its site: business (4), cartography (13), data and databases (13), education (3), environment (9), geography and social sciences (5), geostatistics (8), government (14), health (2), introduction to GIS (29), managing GIS (6), philosophy and design (6), remote sensing (5), software tutorials (18), spatial analysis (4), standards (2), and technical issues (6).

Moving beyond the basic ability to use commercial off-the-shelf software requires the ability to visualize, analyze, manipulate, transform, and interpret geospatial information (skills more advanced than those needed for advanced word processing), capabilities that are comparable in conceptual complexity to those taught in statistics courses. Curriculum designers in the disciplines that employ GIS face questions familiar to those who dealt in an earlier era with the need for students to acquire statistical skills—should they be taught by statistics faculty or should the skills be taught by specialists within the subject department itself? To date, no clear consensus on this recent incarnation of a hoary question has emerged in the country's colleges and universities, so a variety of predominantly ad hoc arrangements are in place.

## NEW CURRICULAR CHALLENGES AND RESPONSES

Since the late 1980s, academic experts at leading research universities have initiated a series of undergraduate curriculum planning projects intended to increase the supply of qualified graduates in GIScience. Interest in such curricula among four-year institutions has waned even as the initiatives have grown increasingly ambitious. Meanwhile, workforce development specialists have attempted to identify the roles that geospatial technology professionals are expected to play, and the competences required for success in those roles.

The National Science Foundation's 1987 solicitation for a National Center for Geographic Information and Analysis (NCGIA) included as one of its four goals "to augment the nation's supply of experts in GIS and geographic analysis in participating disciplines" (NSF, 1987). In 1988, shortly after receiving the National Science Foundation award, the NCGIA consortium developed "a detailed outline for a three-course sequence of 75 one-hour units" (Goodchild and Kemp, 1992, p.310). Fifty leading scholars and practitioners were recruited to prepare draft units. More than 100 institutions worldwide agreed to implement the resulting three-course sequence (introduction to GIS, technical issues in GIS, and application issues in GIS) and to share assessment data with the NCGIA. Lecture notes and laboratory exercises were revised extensively in response to user comments and subsequently published in July 1990 as the NCGIA Core Curriculum (Coulson and Waters, 1991). The Core Curriculum print version was requested by over 1,500 institutions and translated into several languages. In 1995, the NCGIA announced plans to develop a revised and expanded New Core Curriculum in GIScience to incorporate new developments. The revised curriculum was to include at least 176 hour-long units. One-third of the planned units were completed over a four-year period, but the project was abandoned in 2000, because the need for it waned within the higher education community owing to the rapid spread of GIS instruction in North American educational institutions and the proliferation of commercially published textbooks on GIS/GIScience.[1]

In 2001, the National Aeronautics and Space Administration (NASA) mobilized a team of workforce development specialists at the University of Southern Mississippi to investigate the needs of the geospatial industry. The Geospatial Workforce Development Center (GWDC) convened workshops involving representatives of 16 leading businesses, government agencies, and professional societies. Using focus group and group systems methodologies, researchers asked representatives to identify the key skills that successful employees master and the professional roles they are expected to play. The GWDC identified 12 salient roles fulfilled by GIS/GIScience professionals (Table 2-1), and it derived 39 basic competences on which those skills are based, organized under four major headings: Technical, Business, Analytical, and Interpersonal Competences (Table 2-2). Though not wholly comprehensive (intellectual and privacy questions are not included, for example), the list is a sound starting point.

The Model Curricula initiative of the University Consortium for Geographic Information Science (UCGIS) is the latest in a series of national attempts to identify the knowledge and skills needed for success in geospatial technology professions. The related UCGIS Body of Knowledge provides a detailed taxonomy of topics that should be included in any comprehensive GIScience curriculum (Table 2-3). For each unit entry, the Body of Knowledge provides a set of tasks that should be included within the unit. For example the unit on "Elements of Geographic Information" would include a discussion of discrete entities, events and processes, fields in space and time, and integrated models (Sidebar 2-2).

As befits a recently developed specialty, most concern for GIS/GIScience training to date has focused on higher education. The utility of GIS for many tasks and the need for citizens capable of using it for daily tasks will soon make incorporation of GIS into secondary and even primary school curricula a greater concern. Where GIS is currently taught in kindergarten through grade 12 (less than 1 percent of all students), instruction is dominated by the software provided by a single vendor—the Environmental Systems Research Institute (ESRI). Although recent issues of ESRI software are much more user-friendly than earlier versions, the full featured desktop GIS software is designed for use by professionals, not novices. Considerable progress is being made by the vendors to create

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[1] A remote sensing core curriculum project was undertaken under the auspices of the American Society for Photogrammetry and Remote Sensing (Estes et al., 1993; Foresman et al., 1997).

**TABLE 2-1** Twelve Roles Played by Geospatial Technology Professionals as Identified by the Geospatial Workforce Development Center

| Role | Description |
|---|---|
| Applications development | Identify and develop tools and instruments to satisfy customer needs |
| Data acquisition | Collect geospatial and related data |
| Coordination | Interorganizational facilitation and communication |
| Data analysis and interpretation | Process data and extract information to create products, drive conclusions, and inform decision-making reports |
| Data management | Catalog, archive, retrieve, and distribute geospatial data |
| Management | Efficiently and effectively apply the company's mission using financial, technical, and intellectual skills and resources to optimize the end products |
| Marketing | Identify customer requirements and needs, and effectively communicate those needs and requirements to the organization, as well as promote geospatial solutions |
| Project management | Effectively oversee activity requirements to produce the prescribed outcomes on time and within budget |
| Systems analysis | Assess requirements to produce the desired outcomes on time and within budget |
| Systems management | Integrate resources and develop additional resources to support spatial and temporal user requirements |
| Training | Analyze, design, and develop instructional and noninstructional interventions to provide transfer of knowledge and evaluation for performance enhancement |
| Visualization | Render data and information into visual geospatial representations |

NOTE: Roles were defined as subsets of 39 particular competences (Table 2-2). Competences rated as "important" by at least 50 percent of role experts were deemed core competences.

SOURCE: Gaudet et al., 2003, p. 25.

customized desktop and Web-based applications that simplify interaction, thereby flattening the learning curve and becoming more cost-effective in classroom settings. GIS competence, however, is not a component of teacher training in most colleges and universities; the few elementary and secondary school teachers who offer GIS instruction typically have taken ESRI courses (NRC, 2006a). Compounding these impediments and constraints, GIS equipment is costly and expensive to maintain, especially at

**TABLE 2-2** Thirty-Nine Competences Required for Success in Geospatial Technology Professions as Identified by GWDC

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TECHNICAL COMPETENCES
- **Ability to assess relationships among geospatial technologies**
- Cartography
- Computer programming skills
- Environmental applications
- **GIS theory and applications**
- Geological applications
- Geospatial data processing tools
- Photogrammetry
- Remote sensing theory and applications
- Spatial information processing
- **Technical writing**
- **Technological literacy**
- Topology

BUSINESS COMPETENCES
- **Ability to see the "big picture"**
- Business understanding
- Buy-in/advocacy
- **Change management**
- **Cost-benefit analysis and ROI**
- Ethics modeling
- Industry understanding
- Legal understanding
- Organizational understanding
- Performance analysis and evaluation
- **Visioning**

ANALYTICAL COMPETENCES
- **Creative thinking**
- Knowledge management
- Model-building skills
- **Problem-solving skills**
- Research skill
- Systems thinking

INTERPERSONAL COMPETENCES
- Coaching
- **Communication**
- Conflict management
- **Feedback skills**
- Group process understanding
- **Leadership skills**
- Questioning
- **Relationship building skills**
- **Self-knowledge/self-management**

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NOTES: Each professional role listed in Table 2-1 requires a subset of the technical, analytical, business, and interpersonal competences listed here; **Boldface** type indicates competences identified as core competences by GWDC; GI S&T = geographic information science and technology; GWDC = Geospatial Workforce Development Center.

SOURCE: Gaudet et al., 2003.

**TABLE 2-3** Knowledge Areas and Units from the UCGIS GI S&T Body of Knowledge 2006

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**Knowledge Area AM, Analytical Methods**
Unit AM1 Academic and analytical origins
Unit AM2 Query operations and query languages
**Unit AM3 Geometric measures**
**Unit AM4 Basic analytical operations**
**Unit AM5 Basic analytical methods**
Unit AM6 Analysis of surfaces
Unit AM7 Spatial statistics
Unit AM8 Geostatistics
Unit AM9 Spatial regression and econometrics
Unit AM10 Data mining
Unit AM11 Network analysis
Unit AM12 Optimization and location-allocation modeling

**Knowledge Area CF, Conceptual Foundations**
Unit CF1 Philosophical foundations
Unit CF2 Cognitive and social foundations
**Unit CF3 Domains of geographic information**
**Unit CF4 Elements of geographic information**
Unit CF5 Relationships
Unit CF6 Imperfections in geographic information

**Knowledge Area CV, Cartography and Visualization**
Unit CV1 History and trends
**Unit CV2 Data considerations**
**Unit CV3 Principles of map design**
Unit CV4 Graphic representation techniques
Unit CV5 Map production
**Unit CV6 Map use and evaluation**

**Knowledge Area DA, Design Aspects**
Unit DA1 The scope of GI S&T system design
Unit DA2 Project definition
Unit DA3 Resource planning
**Unit DA4 Database design**
Unit DA5 Analysis design
Unit DA6 Application design
Unit DA7 System implementation

**Knowledge Area DM, Data Modeling**
Unit DM1 Basic storage and retrieval structures
**Unit DM2 Database management systems**
**Unit DM3 Tessellation data models**
**Unit DM4 Vector and object data models**
Unit DM5 Modeling 3D, temporal, and uncertain phenomena

**Knowledge Area DN, Data Manipulation**
**Unit DN1 Representation transformation**
**Unit DN2 Generalization and aggregation**
Unit DN3 Transaction management of geospatial data

**TABLE 2-3** Continued

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**Knowledge Area GC, Geocomputation**
Unit GC1 Emergence of geocomputation
Unit GC2 Computational aspects and neurocomputing
Unit GC3 Cellular automata models
Unit GC4 Heuristics
Unit GC5 Genetic algorithms
Unit GC6 Agent-based models
Unit GC7 Simulation modeling
Unit GC8 Uncertainty
Unit GC9 Fuzzy sets

**Knowledge Area GD, Geospatial Data**
**Unit GD1 Earth geometry**
Unit GD2 Land partitioning systems
**Unit GD3 Georeferencing systems**
**Unit GD4 Datums**[a]
**Unit GD5 Map projections**
**Unit GD6 Data quality**
**Unit GD7 Land surveying and GPS**
Unit GD8 Digitizing
Unit GD9 Field data collection
**Unit GD10 Aerial imaging and photogrammetry**
**Unit GD11 Satellite and shipboard remote sensing**
**Unit GD12 Metadata, standards, and infrastructures**

**Knowledge Area GS, GI S&T and Society**
Unit GS1 Legal aspects
Unit GS2 Economic aspects
Unit GS3 Use of geospatial information in the public sector
Unit GS4 Geospatial information as property
Unit GS5 Dissemination of geospatial information
**Unit GS6 Ethical aspects of geospatial information and technology**
Unit GS7 Critical GIS

**Knowledge Area OI, Organizational and Institutional Aspects**
Unit OI1 Origins of GI S&T
Unit O2 Managing the GI system operations and infrastructure
Unit OI3 Organizational structures and procedures
Unit OI4 GI S&T workforce themes
**Unit OI5 Institutional and interinstitutional aspects**
**Unit OI6 Coordinating organizations (national and international)**

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NOTE: **Boldface** type indicates units identified as core units by DiBiase et al. (2006).
[a] A reference datum is a known and constant surface which can be used to describe the location of unknown points. On Earth, the normal reference datum is sea level.

SOURCE: DiBiase et al., 2006. Reprinted with permission from the Association of American Geographers.

## SIDEBAR 2-2
## UCGIS Body of Knowledge Unit CF4: Elements of Geographic Information

The concepts below form the basic elements of common human conceptions of geographic phenomena. Concepts from many units in this knowledge area have been synthesized to create general conceptual models of geographic information. Attempts to resolve the object-field debate have led to attempts to create comprehensive models that bridge these views. Consideration of this unit should also include formal models of these elements in mathematics and other fields. Knowledge area “DM Data Modeling” discusses the representation of these elements in digital models.

**Topic CF4-1 Discrete Entities**

- Discuss the human predilection to conceptualize geographic phenomena in terms of discrete entities;
- Describe particular entities in terms of space, time, and properties;
- Describe the perceptual processes (e.g., edge detection) that aid cognitive objectification;
- Compare and contrast differing epistemological and metaphysical viewpoints on the “reality” of geographic entities;
- Identify the types of features that need to be modeled in a particular GIS application or procedure;
- Identify phenomena that are difficult or impossible to conceptualize in terms of entities;
- Describe the difficulties in modeling entities with ill-defined edges;
- Describe the difficulties inherent in extending the tabletop metaphor of objects to the geographic environment:
    - Evaluate the effectiveness of GIS data models for representing the identity, existence, and lifespan of entities;
    - Justify or refute the conception of fields (e.g., temperature, density) as spatially intensive attributes of (sometimes amorphous and anonymous) entities;
    - Model “gray area” phenomena, such as categorical coverages (also called “discrete fields”), in terms of objects; and
    - Evaluate the influence of scale on the conceptualization of entities.

**Topic CF4-2 Events and Processes**

- Compare and contrast the concepts of continuants (entities) and occurrents (events)
- Compare and contrast the concepts of event and process
- Describe particular events or processes in terms such as identity, categories, attributes, and locations;

- Evaluate the assertion that “events and processes are the same thing, but viewed at different temporal scales”;
- Apply or develop formal systems for describing continuous spatiotemporal processes;
- Describe the actor role that entities and fields play in events and processes; and
- Discuss the difficulty of integrating process models into GIS software based on the entity and field views, and methods used to do so.

**Topic CF4-3 Fields in Space and Time**

- Define a field in terms of properties, space, and time;
- Identify applications and phenomena that are not adequately modeled by the field view;
- Identify examples of discrete and continuous change found in spatial, temporal, and spatiotemporal fields;
- Differentiate various sources of fields, such as substance properties (e.g., temperature), artificial constructs (e.g., population density), and fields of potential or influence (e.g., gravity);
- Formalize the notion of field using mathematical functions and calculus;
- Relate the notion of field in GIS to the mathematical notions of scalar and vector fields;
- Recognize the influences of scale on the perception and meaning of fields;
- Evaluate the representation of movement as a field of location over time [e.g. $<x,y,z> = f(t)$]; and
- Evaluate the field view’s description of objects as conceptual discretizations of continuous patterns.

**Topic CF4-4 Integrated Models**

- Discuss the contributions of early attempts to integrate the concepts of space, time, and attribute in geographic information, such as Berry (1964) and Sinton (1978);
    - Illustrate major integrated models of geographic information, such as Peuquet’s Triad, Mennis’ Pyramid, and Yuan’s Three-Domain;
    - Determine whether phenomena or applications exist that are not adequately represented in an existing comprehensive model;
    - Discuss the degree to which these models can be implemented using current technologies; and
    - Design data models for specific applications based on these comprehensive general models.

SOURCE: DiBiase et al., 2006. Reprinted with permission from the Association of American Geographers.

instructional laboratory scales. Confronting and resolving these obstacles to providing youngsters with basic GIS capabilities at an early age should be part of the profession's current and long-term plans for bolstering GIS/GIScience. The conceptual and strategic ways GIS and GIScience can enhance education, especially at the K-12 level but with more comprehensive implications, are covered in detail in NRC (2006a).

## ASSURING QUALITY IN EDUCATION AND TRAINING

The general absence of standards and accountability for academic certificate programs led one GIScience professional to note that "today anybody can teach anything and call it GIS education. . . . Who knows whether the skills being taught in these programs are needed to become a GIS professional?" (Huxhold, 2000, p.25). Another argued earlier that the "low-level, non-technical" character of undergraduate GIS education produces graduates who are unprepared "to make substantial contributions to the ongoing development of GIS technology" (Marble, 1997, p.28). There remains considerable ambiguity regarding the qualifications of employees in GIScience. Surveying usually requires a license in order to practice. In fact, surveying is usually regulated by the same state board that oversees professional engineering. GIS and GIScience are largely unregulated by states. The qualifications, apprenticeship requirements, and examinations needed to become qualified to be a professional surveyor are well defined and generally follow model laws developed by the National Council of Examiners for Engineering and Surveying. While most states do not license GIScience professionals, South Carolina recently initiated a category of GIS surveyor. It remains to be seen whether other states will adopt similar requirements.

A middle ground between a totally unregulated profession and one that is controlled by state licensure regulation is certification. As the UCGIS Body of Knowledge observes, "Certification is the process by which organizations award credentials to individuals who demonstrate certain qualifications and/or competencies." The American Society of Photogrammety and Remote Sensing (ASPRS) has operated a certification program for GIS for several years. In 2004 the Geographic Information Systems Certification Institute (GISCI) was created to provide systematic oversight of certified geographic information systems (GIS) professionals who meet a set of minimum standards for ethical conduct and professional practice (http://www.gisci.org [accessed 24 May 2006]). More than 1,000 individuals now hold this level of certification. The academic community has been concerned with developing qualified programs that lead to undergraduate and graduate degrees. Several academic departments do offer certificate programs in GIS and related specialties.

The UCGIS Body of Knowledge provides a basis for determining sound content for certification processes (DiBiase et al., 2006).

As of mid-2006, the demand for professional certification in GIS appears to be broad, but not deep. Established accreditation mechanisms are not well suited to the undergraduate sector of the personnel infrastructure, which is inherently multidisciplinary. An innovative approach to accreditation of individual courses and programs in the postgraduate sector may become desirable as offerings proliferate. Portfolio-based certification does not assure individual competence, but may encourage continuing professional development.

## ORGANIZATIONAL CHALLENGES

Academic programs and structures change deliberatively, for sound reasons. Faculty members make long-term commitments to their specialties, and colleges and universities make long-term commitments to faculty members in the forms of tenure and institutional arrangements to organize their productivity. As a new set of ideas and skills with widespread applicability, GIS/GIScience has attracted the attention of a number of traditional academic disciplines (Figure 2-1). Originating in geography and cartography,[2] GIS quickly attracted the interest of the photogrammetry and remote sensing, forestry, geological, and soil science communities, among others. In general, GIS/GIScience was inherently and intuitively attractive to any specialty focused on geographically dispersed resources, and demand for GIS software and professionals who could use it grew rapidly in the public and private sectors. Because of its intrinsic reliance on computer technology and because it presented some novel intellectual and practical challenges, the computer science (and by extension electrical engineering) community also took up GIS/GIScience in the 1980s. Subsequently, a large number of distinct specialties and subdisciplines began to offer GIS courses and address problems in GIScience. Consequently, GIS/GIScience resides in a variety of departments on college and university campuses, most commonly in geography, but in other programs ranging, in all likelihood if a comprehensive list were compiled, from anthropology to zoology (Figure 2-1).

Beyond departments, many colleges and universities have instituted such supradepartmental structures as centers, institutes, interdisciplinary committees and programs, and joint faculty appointments to permit and promote collaboration among departments on topics of common interest.

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[2] Roger Tomlinson coined the term "GIS" and put it into practice in Canada in 1963 (Tomlinson, 1997) prior to Ian McHarg's *Design with Nature* (1969).

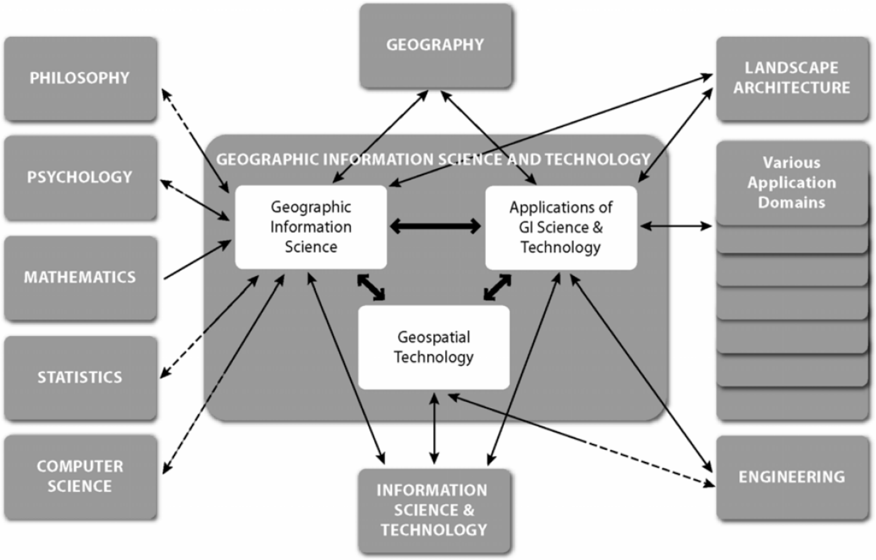

**FIGURE 2-1** The three subdomains comprising the GI S&T domain, in relation to allied fields. Two-way relations that are half-dashed represent asymmetrical contributions between allied fields. The image shows innovations pushing society beyond mapping into a far more versatile and powerful vision of mapping that draws on many additional sciences and technologies.

SOURCE: DiBiase et al., 2006. Reprinted with permission from the Association of American Geographers.

The effectiveness of such varying arrangements in meeting internal college and university needs and the demand for GIS/GIScience professionals varies from place to place. Faculty members may be reluctant to commit fully to GIS/GIScience if the specialty is not a core component of their disciplines, and students attracted to careers in GIS/GIScience may not be served best by programs that are or appear to be ad hoc in nature, secondary in stature, or both. Among academic institutions, private institutions seem to have instituted structural changes more rapidly in response to the opportunities offered by GIS/GIScience, perhaps owing to greater flexibility to reprogram resources. Public colleges and universities have moved more slowly, owing perhaps to their generally larger sizes and stronger tradition of sharing governance between faculty and administrators (with notable exceptions, such as the University of Texas at Dallas [Sidebar 1-5]). For-profit academic institutions, less tied to traditional curricula and organizational forms, are able and willing to respond quickly to student demand and the markets for their products. One example of private education moving to meet market needs was the two-day workshop on “Unleashing the Power of GIS and GPS” offered at the 2006 annual meeting of the Association of American Geographers by Informa Learning (formerly TFI Learning), an international provider of specialist information and services for the academic, professional and business communities. This type of offering is likely to be imitated more frequently in the future.

# 3

# GIS/GIScience Research Needs

National needs in GIS/GIScience span a wide spectrum of research topics, ranging from applications through abstract theoretical considerations in cartography, computer science, geography, military science, philosophy, psychology, intelligence and security studies, and sociology, among other disciplines. Some of the dilemmas evoked by GIS technology and its existing and proposed applications arouse serious public policy questions and debate. The suitability of existing organizational arrangements to meet the demands inspired by GIS/GIScience can be questioned with specific reference to college and university structure, research funding mechanisms, and research agenda setting.

## PRACTICAL AND THEORETICAL CHALLENGES

Geographic information systems have revolutionized the ways society handles geospatial information, allowing the automation of what were previously tedious and inaccurate methods of map analysis, the construction of sophisticated simulations of real systems, and the visualization of geospatial information in new and exciting ways. Much research is still needed, however, to handle new and potentially powerful datasets, to exploit research advances that have been made but not implemented in ways that are easy to use, and to provide effective tools in support of spatial decisions. In addition to enjoying new ways of collecting, viewing, and manipulating more accurate and more precise geographic data, geographic information scientists continue to improve their capacities to create higher-dimensional datasets by integrating data from multiple sources. Maintaining or accelerating current rates of improvement in data integration constitutes a major challenge, as does grappling with the related questions of access to data (who can have what, when, and where), data preservation (what and how much to keep and how to organize what is kept) and providing access to stored information.

The Mapping Science Committee's report *Weaving a National Map* (NRC, 2003b) commented on several of the data characteristics envisioned in the USGS plan for the National Map. The committee used the metaphor of blankets and quilts to describe the complex nature of multiresolution geospatial information that is inevitable in today's world. While organizations such as the Bureau of the Census must work with uniform blankets of a specified scale for the entire nation, local governments continuously create quilts of extremely high resolution for property records and infrastructure management. The committee identified this as a major issue, noting that "the edge-matching problems caused by variable resolution will be severe and not always solvable" (NRC, 2003b, p.51). This is the type of practical technical issue that is likely to be addressed by the new Center of Excellence in GIScience that is being created by the National Geospatial Programs Office (USGS, 2005). The research agenda for this center is being created with assistance from the NRC's Mapping Science Committee.

While GIS software has demonstrated its importance and functionality in business and government applications that rely on the creation, maintenance, and retrieval of spatially referenced information, applications in some scientific domains have been more challenging. For example, atmospheric, hydrologic, and environmental scientists often need to model dynamic processes that occur in three dimensions above or below Earth's surface. The first "Environmental Modeling with GIS" meeting was organized in 1993, and a series of scientific conferences have followed. In order to meet the specialized needs of researchers in these communities, software vendors have expanded their tools for analysis, interpolation, and flow modeling. They have also developed interactive tools that enable a researcher to visually develop process models that link data inputs to procedures and output. These tools enable a hydrologist to create a surface flow model that can run with standard GIS software and also be shared with other colleagues for further refinement and evaluation.

Clearly, three-dimensional virtual globes such as Google Earth assist with the visualization of these model results. They also provide an excellent way to discover real-time data sources such as USGS stream gauges. The challenge of extending existing GIS tools into complex dynamic environments is being addressed by a new GIS initiative at the Center for Capacity Building in the University Corporation for Atmospheric Research (UCAR) within the National Center for Atmospheric Research

(NCAR) in Boulder, Colorado. The main objective of this initiative is to promote and support the use of GIS as both an analytic and an infrastructure tool in atmospheric research in order "to foster collaborative science, spatial data interoperability, and knowledge sharing with GIS." A workshop in 2002 explored crucial issues related to integrating weather and climate data with complementary information from the physical sciences, social sciences, and related areas of the geosciences. A group of UCAR and NCAR scientists and engineers have been exploring opportunities for using GIS to enhance knowledge sharing and integration for research, applications, and education (http://www.gis.ucar.edu/initiative.html [accessed May 24, 2006]).

Some additional problems and questions for which more ideas and more trained people are needed are

- Ways to map and analyze such dynamic phenomena as new road construction, thunderstorm and hurricane development, or animal, human, and inventory movements in near real time;
- Developing real-time maps for handheld devices, including audio capabilities;
- Testing possible relationships between disease outcomes and environmental, demographic, and social indicators to predict the spread of disease through human, animal, or plant populations;
- Refining navigational information for the sight impaired;
- Analyzing networks to identify choke points and critical nodes, and the potential effects of removing or blocking selected links in a road network or for evacuation during emergencies;
- Investigating why past data-sharing efforts failed and identifying the types of institutions and mechanisms (e.g., mandates, incentives, regulations) most likely to succeed given current interaction among federal, state, local, and private organizations;
- Methods for analyzing vast repositories of geospatial data in search of patterns and anomalies to uncover unknown associations between and among attributes; and
- Portraying greater detail in response to (1) using voice or gesture activation, (2) pointing and clicking (linking and brushing) on features of an image that are linked to supplemental information (e.g., audio files), or (3) zooming to a higher-resolution image.

## Privacy Issues

Many geospatial datasets contain sensitive information and consequently are restricted or licensed. For example, an insurance company's database of property information is one of its most valuable and protected assets, yet those data would be invaluable to emergency response organizations during a fire or natural disaster. Other data, while extremely useful to fire and police organizations, could be dangerous in the wrong hands. Research is needed to identify both the technical advances required to create systems for sharing restricted data and to formulate business models that simultaneously support and constrict access to sensitive datasets. In fact, the emergence of GIS/GIScience could be taken as a stimulus for taking a fresh look at the entire concept of privacy relative to geospatial data, rather than creating a set of ad hoc solutions.

### Interoperability

Even though geospatial data are created for numerous purposes by a variety of public and private organizations using different standards and software, it is important to maximize the interoperability of data and software. Many types of geographic data are created by a variety of public and private sector organizations. For example, when anthrax spores were detected in New Jersey postal facilities, state health officials scrambled to identify building locations, potentially affected neighborhoods, and building floor plans for inclusion in the state GIS in order to facilitate analyses. Databases used by state officials were often incompatible with local information sources. The result was masses of datasets with no way to integrate them quickly, accurately, or efficiently. The optimal benefits of these data will be realized and the risks they pose for society will become more evident when they can be accessed, integrated, and manipulated simultaneously by diverse organizations coordinating their activities.

## GIS/GISCIENCE AND SOCIETY[1]

As with any new technology, one of the challenges facing societies that employ geographic information systems is that of ensuring maximum benefits while minimizing the risks of misuse. Geographic data can be misused, either deliberately or through inadvertence, as often occurs when individuals innocent of the principles of mapping portray data inappropriately. The collection of geographic data and the ability easily to copy digital data can raise questions about who owns what data, for how

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[1] The term "GIStudies" has been proposed to designate research on the uses to which GIS and GIScience are put and investigations of the interactions between GIS/GIScience and societies. Though not widely adopted, the distinction does identify a critical realm for scientific and policy research, either independently or as a focus within the general topic of science, technology, and society analyses (Forer and Unwin, 1999).

long, and for what purposes. Numerous questions regarding intellectual property with respect to geographic data are being contested, and many more will arise in the future as the use and value of geographic data increase (NRC, 2004).

Geographic information systems and geographic information science appear to be benign technologies, but some of their applications have been questioned; as is true of any technology, GIS, though neutral in and of itself, can be used for pernicious ends. GIS makes it easier for marketers, for example, to pinpoint likely customers for purposes of advertising, but the same data and techniques can be used to profile individuals and groups for surveillance or for robbery. Because individuals can be profiled by linking data to their places of residence, the collection and comparison of geographic information can result in the erosion of individual privacy (Monmonier, 2002). At what appears now to be an extreme, GPS chips can be embedded in animals, children, parolees, and rental cars, making it possible to track their movements continuously, leading to the possibility of forms of geoslavery, if some individuals acquire the capability to control the movements or locations of others using monitoring technologies (Dobson and Fisher, 2003). Mapping viewsheds (the places that can and cannot be seen from a specific point) on a battlefield or for surveillance may be good or bad, depending which side of the war a person is fighting on or a person's attitude toward general-purpose surveillance. Applications that are highly beneficial in many situations could be ominous in the hands of a totalitarian government (NRC, 1997). The country needs GIScience professionals who have a sufficient background in the policy and social sciences to be sensitive to the full array of positive and negative applications their new technologies enable.

In the final analysis, the mapping sciences exist to provide society with geospatial information, and their success in doing so must be the basis of any measure of their value to society. The world of geographic information creation has changed dramatically over the past few decades, as a result of new technologies for sensing, acquiring, assembling, validating, disseminating, and using geospatial information. Many problems and questions remain, however, and there are many ways the supply of society's geographic information could be improved.

## RESEARCH INFRASTRUCTURE

The country's research infrastructure for GIS/GIScience is poorly developed. There exists no core outside the few federal agencies that traditionally had national mapping responsibilities. Within the National Science Foundation (NSF), the major source for basic science funding has come from the Geography and Regional Science program in the Social, Behavioral, and Economic Sciences Directorate, from various programs in the Computer and Information Sciences Directorate, and from the Education and Human Resources Directorate. No single NSF program has primary responsibility for geographic information systems and geographic information science. The NSF implicitly recognized the need for coordination of GIS/GIScience in the appointment in late 1998 of a GIS coordinator, but the position was not filled when the incumbent left the agency shortly thereafter.

In 1999, the NSF sponsored a workshop on emerging research themes in GIScience (Mark, 1999). The workshop clearly differentiated two types of research associated with GIS: (1) scientific research using GIS, and (2) research that advances GIScience. Both kinds of research are often intertwined, as they frequently are in the discussions of the UCGIS. In practice one might add a third kind of research: using GIS to implement the results of science in the formulation of policy, in spatial decision support systems, for example. The workshop report identified four research issues facing GIScience: (1) the integration of data, (2) analysis of the relationship between data and scale, (3) the implementation of models of process, and (4) usability. The workshop report also recommended that:

- NSF recognize GIScience as a coherent research specialty and establish a funding center for it as soon as possible;
- Both basic GIScience and research using GIS be supported by the new unit to promote integration of these related research efforts;
- NSF establish an internal task force consisting of representatives from all its directorates and the Office of Polar Programs, charged to meet regularly and ensure that GIScience links to all relevant parts of the foundation and benefits from their operations; and
- NSF appoint a multidisciplinary advisory panel of non-NSF personnel to assist in defining, implementing, and evaluating the new unit’s effectiveness.

Other federal agencies with potential interest in funding research in the mapping sciences include the National Geospatial-Intelligence Agency, the U.S. Geological Survey, the Bureau of the Census, and the National Aeronautics and Space Administration. Many other agencies have supported specific GIS applications, including the National Institutes of Health and the Department of Justice. Yet, no central, coordinated office for funding the mapping sciences exists within the federal government.

Nevertheless, funding opportunities for GIS/GIScience exist in numerous government agencies. Mapping scientists have successfully collaborated with scientists from other disciplines to compete for major funding on projects in which geospatial data, technologies, and principles are indispensable. Almost no funding for basic research has been forthcoming from private corporations. The research conducted by private firms has for the most part been kept as privileged data, shared only when economic advantages are perceived. Examples of private/public funding exist in allied fields in Canada and Europe. ERTICO (Intelligent Transportation Systems and Services—Europe) is a not-for-profit, public-private partnership whose mission is to implement intelligent transport systems and services in Europe. ERTICO's projects are financed by annual fees from its partners and by project funding from organizations such as the European Commission. In the United States, a prominent example of public-private funding is the collaboration between private companies and the U.S. Food and Drug Administration (FDA). The 1992 Prescription Drug User Fee Act (PDUFA) authorizes FDA to collect fees from companies that produce human drug and biological products that FDA reviews.

Perhaps a similar scheme would work in the United States for funding GIScience research, with a nonprofit entity such as the Open Geospatial Organization disbursing funds in support of a consensus research agenda. The organization would need base funding from the federal government and from agencies and private firms interested in the results of specific research agenda topics. One could even imagine that the nonprofit entity might be supported by modest taxes on location-based services, such as one cent per month on every mobile telephone or a flat tax on each GPS device. In the absence of this or some other form of augmented funding, GIS/GIScience will continue to be more fragmented than necessary.

## EXECUTING RESEARCH AGENDAS

Since 1990, several groups have proposed no fewer than 11 overarching research agendas for GIS/GIScience (Table 3-1). The lists of commissions of the International Cartographic Association (http://www.icaci.org/en/commissions.html [accessed 24 May 2006]) and the International Society for Photogrammetry and Remote Sensing (http://www.isprs.org/tcwg.html [accessed 24 May2006]) provide insights into current research practice in these specialties within the mapping sciences. The most recent agenda prepared by the UCGIS lists a comprehensive set of long- and short-term major topics (Sidebar 3-1); the National Research Council's Mapping Sciences Committee has also put forth a list of research priorities for the National Geospatial-Intelligence Agency (NGA) (Sidebar 3-2).

**TABLE 3-1** Proposed GIS/GIScience Research Agendas, 1988-2005

| Date | Proposed By |
|---|---|
| 1988 | David Rhind (1988) |
| 1989 | National Center for Geographic Information and Analysis (1989) |
| 1992 | National Center for Geographic Information and Analysis (1992) |
| 1996 | University Consortium for Geographic Information Science (1996) |
| 1999 | National Computational Science Alliance (1999) |
| 2000 | International Cartographic Association (2000) |
| 2002 | University Consortium for Geographic Information Science (2004) |
| 2002 | Ohio State University (2002) |
| 2003 | National Research Council (2003a) |
| 2004 | Robert McMaster and Mark Monmonier (2004) |
| 2006 | National Geospatial-Intelligence Agency (NRC, 2006b) |

The numerous efforts to devise an overarching research agenda parallel new developments in technology and its applications. At the same time, they reflect an increased interest in investigating interactions between GIS technology and society, each in its own way resting on varying conceptions of individuals, computers, mapping, and society, with GIScience at their common core (Egenhofer et al., 1999; Goodchild et al., 1999; Sheppard et al., 1999). Research about the individual is dominated by cognitive science and focuses on understanding spatial concepts, learning and reasoning about geographic data, and interactions between humans and computers. Research about computers is dominated by representation, adoption of new technologies, computation, and visualization. Research about society addresses the effects of technologies and societal concerns about their use.

Differences among the research agendas for GIS/GIScience that have been proposed over the last 30 years generally reflect the varying focuses of the groups that have put them forward, and many common elements transcend both the multiple disciplines engaged in GIS/GIScience and the time that has elapsed since geographic information systems moved beyond the experimental stage. In some respects, the first formal research agenda was proffered in the 1987 National Science Foundation solicitation for proposals for the National Center for Geographic Information and Analysis (NCGIA). Formulated on the basis of broad consultation with the contemporary GIS research and applications community, the solicitation listed four goals for the new center (NSF, 1987):

- Advancing the theory, methods, and techniques of geographic analysis based on geographic information systems;

## SIDEBAR 3-1
## UCGIS Research Agenda

**Long-term Research Challenges**

- Spatial ontologies
- Geographic representation
- Spatial data acquisition and integration
  - Remotely acquired data and information in GIScience
- Scale
- Spatial cognition
- Space and space/time analysis and modeling
- Uncertainty in geographic information
- Visualization
- GIS and society
- Geographic information engineering
  - Distributed computing
  - The future of the spatial information infrastructure
  - Geospatial data mining and knowledge discovery

**Short-term Research Priorities**

- GIS and decision making
- Location-based services
- Geoslavery
- Identification of spatial clusters
- Geospatial semantic web (a web of geospatial data that can be processed by machines)
- Incorporating remotely sensed data and information in GIS
- Geographic information resource management
- Emergency data acquisition and analysis
- Gradation and indeterminate boundaries
- Geographic information security
- Geospatial data fusion
- Institutional aspects of spatial data infrastructures
- Geographic information partnering
- Geocomputation
- Global representation and modeling
- Spatialization
- Pervasive computing
- Geographic data mining and knowledge discovery
- Dynamic modeling

SOURCE: UCGIS, 2004; McMaster and Usery, 2004.

## SIDEBAR 3-2
## NGA GIS/GIScience Research Priorities

The list of research priorities for the National Geospatial-Intelligence Agency (NGA) prepared by the NRC Mapping Sciences Committee (NRC, 2006b) lists 12 salient tasks:

- Assimilation of new, numerous, and disparate sensor networks within the tasking, processing, exploitation and dissemination process;
- Spatiotemporal data mining and knowledge discovery from heterogeneous sensor data streams;
- Spatiotemporal database management systems;
- Process automation and human cognition;
- Visualization;
- High-performance grid computing for geospatial data;
- Image data fusion across space, time, spectrum, and scale;
- Role of text and place-name search in data integration;
- Reuse and preservation of data;
- Detection of moving objects from multiple heterogeneous intelligence sources;
- Geospatial intelligence ontology; and
- Multilevel security.

The mission of the NGA—until 2003, the National Imagery and Mapping Agency—is to provide timely, relevant, and accurate geospatial intelligence to support national security. Although some of its priorities are distinct to its specialized mission, many of them overlap to a greater or lesser degree with GIScience research priorities identified by other groups.

SOURCE: NRC, 2006b.

- Augmenting the nation's supply of experts in GIS and geographic analysis;
- Promoting the diffusion of analysis based on GIS throughout the scientific community; and
- Acting as a clearinghouse for disseminating information on research, teaching, and applications.

These goals were to be met by addressing five priority research topics each containing a number of specific tasks (Abler, 1987):

1. New modes and methods of spatial analysis
   - — Social science applications for GIS-based spatial analysis
   - —Error and error propagation
   - —Nontraditional statistics
2. A general theory of spatial relationships
   - —Theory of spatial relationships
   - —Nonplanar relationships among multiple objects
   - —Efficient data storage structures
   - —Structures for volumetric data
   - —Structures for time-dependent data
   - —Methods for integrating heterogeneous data
   - —Techniques for redefining data
   - —Translations among different locational schemes
3. Artificial intelligence and expert systems in GIS
   - —Automated data entry
   - —Database summaries and indexes
   - —Map evaluation and interpretation
   - —Intelligent geographical information systems
4. Visualization
   - —New options for color and motion
   - —Three-dimensional maps
   - —Showing error on maps
   - —Noncartographic means of displaying spatial relationships
5. Social, economic, and institutional issues
   - —GIS adoption and implementation
   - —Costs and benefits of GIS
   - —Information access
   - —Privacy
   - —Legal questions

Many, if not most, of the long-term research challenges and short-term research priorities listed in the most recent iteration of the UCGIS research agenda (Sidebar 3-1) persist in one form or another and fit under one or more of the rubrics contained in the 1987 NSF solicitation. For the most part, the NGA priorities (Sidebar 3-2) appear to be agency mission-specific instances of the more general priorities identified in the UCGIS tabulation. The persistence of many elements (often indeed in advanced and refined formulations) of the 1987-1988 statement of priorities is perhaps to be expected in a newly emerging specialty. Alternatively, their persistence may suggest that a fresh look at the most recent iteration is in order. The UCGIS research agenda is an attempt at a consensus program based on a generally open and broad participatory process. In the committee's judgment, it should soon be endorsed and pursued by the

U.S. GIS/GIScience community or modified as needed to make it acceptable to that community. Broad support throughout the GIS/GIScience research and applications community would be a major step toward garnering increased support for GIS/GIScience research and toward producing the well-qualified GIS/GIScience professionals the country needs.

# 4

# Recommendations

The overriding challenge for society with respect to GIS/GIScience is to ensure the next generation of scientists and technologists is produced in large numbers and is well prepared to build on the impressive progress achieved during the last 30 years. The committee offers the following recommendations in response to that challenge:

1. The mapping sciences, despite numerous attempts to formulate one, still lack a coherent, comprehensive research agenda. Scientists from the multiple disciplines engaged in GIS/GIScience should make a concerted effort to achieve consensus on such an agenda, using the most recent outline proposed by the University Consortium for Geographic Information Science (UCGIS) as a point of departure.
2. Private-public funding models should be thoroughly investigated and, where feasible, should be applied to GIScience research in the United States. A possible model is Intelligent Transportation Systems and Services—Europe (http://www.ertico.com/ [accessed 24 May 2006]).
3. GIScience should be recognized as a coherent research specialty. The National Science Foundation should take responsibility for coordinating funding for GIS and GIScience, as recommended in Mark (1999).
4. Collaboration should be promoted among academic disciplines, private companies, and federal, state, and local government agencies to create a virtual network of GIScience researchers, laboratories, centers, and corporations. For example, an Institute for Geographic Information Science could be established under the joint auspices of the UCGIS (Sidebar S-2), representing major research universities, and the Open

Geospatial Consortium (OGC), representing industry, government agencies and laboratories, and universities (Sidebar S-3).

5. The country's colleges and universities must become more flexible if they hope to keep pace with the GIS/GIScience industry and with government programs. Industry and government have taken the lead in developing and implementing digital approaches to map production; academic institutions follow as much as they lead. Accordingly:

a. Academic institutions should reconsider their internal organization and reward structures to make them more responsive to emerging specialties like GIS/GIScience, and to reward (or at least not penalize) faculty members who pioneer innovative topics and who engage in collaborative work with government agencies and private firms. Where credit for enrollments impedes cross- and multidisciplinary education, credit-sharing mechanisms should be employed. Devising institutional arrangements that favor robust GIS/GIScience and the funds necessary to sustain it will yield large dividends in the form of ready employment for undergraduates and advanced-degree graduates.

b. To meet the need for trained GIS/GIScience professionals and an informed citizenry, education programs in GIS/GIScience should be implemented at all levels of education (K-20, with special attention at the K-16 levels) in the United States. These programs should cut across traditional disciplinary borders and employ the latest technologies. The numerous ways GIS and GIScience can enhance spatial thinking (NRC, 2006a, pp.166-216) offer promising mechanisms for accomplishing that task, especially at the K-12 level. Maximum use should be made of the National Science Foundation's programs for Research Experiences for Undergraduates (REU) and Research at Primarily Undergraduate Institutions (RUI) in pursuing this goal (NSF, 2006a,b).

c. The National Geospatial-Intelligence Agency and the National Science Foundation are to be commended for their recent programs encouraging needed research and organizational changes in academia. Such programs should be expanded and broadened to ensure that the country produces enough trained professionals to lead GIScience in the future.

d. More government-private, industry-academic partnerships are needed, and industry should consider funding relevant academic research and training to assure continued future innovation. The success of the NCGIA in obtaining private-sector funding for its work provides a model for such efforts and illustrates the benefits of academic-federal-industry coalition building. A government-industry-academic board should be established to promote such relationships, perhaps under the auspices of UCGIS and OGC or as part of the Institute for Geographic Information Science proposed in Recommendation 4. Industry and government could also expand their existing contributions to universities of serving on advisory boards, offering internships, and serving as adjunct faculty.

e. The UCGIS Model Curricula Body of Knowledge[1] should be maintained and widely adopted and implemented, since it provides a basis for determining the eligibility of education achievement claims for GIS certification.

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[1] http://www.ucgis.org/priorities/education/modelcurriculaproject.asp (accessed 24 May 2006).

# 5

# Afterword

The transformations of science and daily life that have accompanied the shift to digital mapping and location-based services during the last 30 years are ongoing and profound. The growing use of technologies related to maps and location, particularly those that have been enabled by GIS and GIScience, have stimulated the transformation of numerous government agencies at the federal, state, and municipal levels. Hundreds of new software and service firms have been started to meet (and create) the demand for services based on location. Even family life has been affected. Parents can now track and monitor their children's locations using the offspring's GPS-capable telephones. It is becoming difficult to think of a realm of economic, social, or political life that has not been affected by GIS and GPS digital technologies and the maps or mapping processes upon which they are based. It is equally difficult to see any end to the demand for more accurate, more precise geographic data and for well-trained professionals to provide and process them. In digital technologies generally, supply and innovation create new demand as much as they respond to existing demand.

A great strength of GIS/GIScience today resides in the happy circumstances that GIS and GIScience were largely innovated in North America and applied most vigorously in the United States, giving the country a head start and a leading role in the continued development of the burgeoning technologies. That lead persists, but it is being challenged in Europe and Asia. The Achilles heel of GIS/GIScience today is the country's continued inability to produce in adequate numbers the personnel needed to maintain the country's leadership in GIS/GIScience applications and research, a situation that recently led the U.S. Department of Labor to designate geotechnology (largely GIS/GIScience) one of the three most important emerging and evolving employment fields (with nanotechnology and biotechnology) in the country (Seitzen, 2004). The recent announcement of such new user-friendly and inexpensive mapping services as Google Earth, Placepedia, Flickr, and others guarantee that the strong demand for geographically referenced data and for competent professionals to manage it will continue indefinitely. The country is now at only the beginning of the democratization of map-based technologies.

During the last 30 years, many government agencies and private-sector firms have instituted major changes in their structures and organization in response to the opportunities GIS/GIScience offer and to the imperatives its effective or profitable use impose. The sector the least altered in response to digital mapping is the academic world, a major concern owing to the academic sector's crucial role in producing the labor force needed to assure continued global leadership and domestic progress in GIS/GIScience. GIS/GIScience education and research resides in different academic departments or programs in the country's colleges and universities, depending largely on which unit was home to an early adopter of GIS. Institutional inertia has too often left GIS and GIScience scattered in various locations on each campus, leading to variations in GIS/GIScience curricula that depend on which program is offering a course, despite the existence of model curricula and of recent models of centralized, coherent GIS/GIScience programs. Variations in approach and emphasis raise concerns regarding the balance between training students to use propriety software without much idea of what the software is actually doing, versus the education needed to know when and how software should be employed, and more important, when it will not yield valid or useful results. Widespread variations in course and curriculum content also impede the design of acceptable and effective mechanisms for certifying the competence of GIS/GIScience professionals.

GIS and GIScience offer the country's colleges and universities great opportunities now and for the foreseeable future. Responding quickly and innovatively to those opportunities will require institutional restructuring as well as the investment of scarce funds, but handsome returns await the institutions willing and able to make the necessary adjustments. The current and future demand for GIS/GIScience professionals seems unlimited, implying employment for all the well-trained students a college or university can produce. Institutional investments in faculty specializing in GIScience will ensure that colleges and universities that make such investments will help shape the evolving GIS/GIScience research agenda in ways consistent with their home institutions' missions. Funds for GIS/GIScience research are not abundant in relation to need, but they are less scarce than in other specialties, and faculty members pursuing GIS/GIScience will have significantly better than average chances of capturing external research support.

Owing to their pervasive and increasing use in many aspects of economic, political, and social life—as well as in environmental analysis—institutions that develop strong programs in GIS/GIScience will serve society well by educating students who will increasingly need a basic understanding of GIS/GIScience in order function effectively as citizens, by educating the teachers who will begin that process in elementary and secondary schools, and by hiring faculty members who can address the science policy dilemmas arising from the growing use of GIS and GIScience.

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# Appendixes

# Appendix A

# Biographical Sketches of Committee Members and Staff

**Joel L. Morrison**, *chair*, is emeritus professor in the Department of Geography at Ohio State University. Previously, he was director of Ohio State's Center for Mapping and was chief of the Geography Division of the U.S. Bureau of the Census, with a brief special assignment to the National Science Foundation in the Geography and Regional Science Program of the Social, Behavioral, and Economic Directorate. Dr. Morrison also was a senior administrator at the U.S. Geological Survey. Dr. Morrison has been active in the development of geospatial data standards, bringing together diverse efforts within the United States to create the Spatial Data Transfer Standard. As chairman of the International Cartographic Association's Commission on Spatial Data Quality, he coauthored "Elements of Spatial Data Quality." Dr. Morrison earned his B.A. cum laude from Miami University, Oxford, Ohio, in 1962; his M.S. in geography from the University of Wisconsin-Madison in 1964; and his Ph.D. in Geography-Cartography with a minor in statistics from the University of Wisconsin-Madison in 1968. He is the recipient of the Carl Mannerfeld Gold Medal from the International Cartographic Association, the Meredith Burrell Award from the Association of American Geographers, and the James Anderson Award in Applied Geography. He is a former member of the National Research Council's Mapping Sciences Committee.

**John S. Adams** is professor of geography at the Department of Geography and professor of urban and regional planning at the University of Minnesota. He is a leading population and urban geographer of the United States and Eastern Europe, and has written extensively on the forces that shape large metropolitan areas and their consequences for people within them. He also has been a pioneer in the spatial analysis of population data for application in state and national policy making. He has conducted policy research at the University of California, Berkeley, the Bank of America World Headquarters in San Francisco, and taught at several universities in Eastern Europe and Russia. His current research includes exploring the dynamics of the Minneapolis-St. Paul metropolitan region, sponsored and financed by the Minnesota Department of Transportation, the Metropolitan Council, and the University of Minnesota's Center for Transportation Studies, and carried out with a team of graduate students in geography. He received a B.A. in economics (1960) and an M.A. in economics (1962) from the University of St. Thomas (St. Paul, Minn.), and a Ph.D. in urban economic geography (1966) from the University of Minnesota.

**Sarah W. Bednarz** is an associate professor of geography at Texas A&M University. She teaches courses on human geography, the geography of Texas, and geographic education. Her research interests focus on cognitive science and geography. As one of the primary authors of the National Geography Standards, she developed the materials on geographic skills and other components of the project. She also served on the team that developed the framework for the 1994 National Assessment of Educational Progress Geography Assessment. She has served as the Association of American Geographers representative to the Geography Education National Implementation Project and is co-coordinator of the Texas Alliance for Geographic Education. For two summers Dr. Bednarz served on the staff of the Educational Technology Leadership Institute, a teacher-training project cosponsored by the National Geographic Society and IBM. She is currently a member of the geosciences team supervising a group of graduate students in spatial sciences for the NSF-funded Informational Technology in Sciences Center at Texas A&M University. She received her bachelor's degree in geography at Mount Holyoke College, Massachusetts, an M.A.T in geography from the University of Chicago, and completed a Ph.D. at Texas A&M.

**Max J. Egenhofer** is the director of the National Center for Geographic Information and Analysis at the University of Maine, the Libra Professor of the College of Engineering, professor in Spatial Information Science and Engineering, and cooperating professor in computer science. Dr. Egenhofer's research interests include spatiotemporal reasoning, user interfaces for geographic information systems, the design of spatial database systems, and mobile spatial information appliances. He has authored or coauthored articles in journals, books, and conference proceedings relating to GIS and computer science on various aspects of GIS design. He received an M.S. in surveying engineering from the University of Stuttgart, Germany, in 1985, and his Ph.D. from the University of Maine in surveying engineering in 1989.

**Mark N. Gahegan** is a professor of geography and affiliate professor at the School of Information Science and Technology at The Pennsylvania State University. He has been a faculty member at The Pennsylvania State University since 1998, and his research interests include geographic information science (GIS), visualization, semantic models of geography, geocomputation, digital remote sensing, artificial intelligence tools, spatial analysis, Voronoi diagrams, databases, and qualitative reasoning. His editorial roles include International Journal of GIS; Transactions in GIS; Computers, Environment, and Urban Systems; and Computers & Geosciences. He is a technical representative to the Open Geospatial Consortium and associate director of the GeoVista Center at Penn State. He received his B.S. at the University of Leeds, U.K., and his Ph.D. at Curtin University, Australia.

**Henry L. Garie** has been with the New Jersey Office of GIS, which is responsible for coordinating the development and use of GIS tools and spatial data, since 1999. Dr. Garie previously served as executive director of Geospatial One-Stop, an e-government initiative sponsored by the federal Office of Management and Budget. In 2001, he was appointed to the New Jersey Geographic Information Council. He led a State agency GIS partnership that included membership of all 17 cabinet-level agencies and served as chair of the New Jersey State Mapping Advisory Committee. Before being named as state GIS coordinator in 1999, he directed the GIS Program in the N.J. Department of Environmental Protection from 1986 through September 1999. Dr. Garie is a past president of the National States Geographic Information Council (1997-1998) and served on the Mapping Sciences Committee of the National Research Council (1998-2000). He was a member of the Steering Committee for the 1999 National Geo-Data Forum and has served on numerous advisory groups working with the Federal Geographic Data Committee. He has an M.S. in environmental sciences from Rutgers University.

**Michael F. Goodchild** is a professor of geography at the University of California, Santa Barbara, chair of UCSB's Center for Spatially Integrated Social Science, and chair of the Executive Committee of the National Center for Geographic Information and Analysis. He received his B.A. in physics from Cambridge University and his Ph.D. in geography from McMaster University. He taught at the University of Western Ontario for

19 years before moving to his present position in 1988. His research interests focus on the generic issues of geographic information, including accuracy and the modeling of uncertainty, the design of spatial decision support systems, development of methods of spatial analysis, and data structures for global GIS. His publications include the two-volume text *Geographic Information Systems: Principles and Applications.* He currently is a member of the Geographical Sciences Committee and formerly served as chair of the National Research Council's Mapping Science Committee. In 2002, he was elected to the National Academy of Sciences.

**Kathleen (Kass) Green** is the president of Alta Vista Company where she acts as an independent consultant on geospatial strategy, technology and policy issues to private, educational, and public organizations. She formerly served as the president of Space Imaging Solutions, a division of Space Imaging LLC. Prior to joining Space Imaging, Ms. Green was president of Pacific Meridian Resources, a GIS consulting firm she cofounded in 1988 and sold to Space Imaging in 2000. Ms. Green's background includes over 29 years of experience in natural resource policy, economics, GIS analysis, and remote sensing. She is the author of numerous articles on GIS and remote sensing and has coauthored a book on the practical aspects of accuracy assessment. Ms. Green is the current vice president of the American Society of Photogrammetry and Remote Sensing, and is a past president of the Management Association for Private Photogrammetric Surveyors, an organization of private mapping firms dedicated to advancing the mapping industry. She received a B.S. in forestry and resource management from the University of California, Berkeley (1974), an M.S. in resource policy and management from the University of Michigan, Ann Arbor (1981), and advanced to candidacy toward her Ph.D.in wildland resource science from the University of California, Berkeley.

**Michael Tait** joined Environmental Systems Research Institute Inc. (ESRI) in 1989 as a project manager/consultant in the Professional Services Division and is now Director of the Internet Solutions Division. He is responsible for the development of ESRI's ArcIMS product and Geography Network development activities and oversees a staff of software programmers and product specialists that is responsible for design, development, and release of ESRI's ArcIMS software products. Prior to joining ESRI, Mr. Tait worked for the Planning Department for the City of Austin, Texas (1985-1989). He is skilled in GIS/database application development, database development and management, data model design and development, and data applications programming and implementation. He received a B.A. in geography and an M.S. in community and regional planning with an emphasis in planning information systems from the University of Texas at Austin.

**Nancy Tosta**, vice president of Ross & Associates Environmental Consulting Ltd. in Seattle, Washington, has over 25 years of experience managing and providing leadership on international, national, state, local, intergovernmental, and regional initiatives to use, integrate, and coordinate technology for addressing human and natural resource management issues. She has expertise in policy formulation and standards, intergovernmental and interagency technology initiatives, organizational change management, funding and research strategies, information integration and dissemination, and GIS needs assessments and applications. Prior to working in the private sector, she was the special assistant to the secretary for geographic data coordination, Department of the Interior; chief/staff director, USGS National Mapping Division; and deputy director, State of California Teale Data Center. Ms. Tosta received her M.S. in soil science (1976) and B.S. in soils and plant nutrition (1974) from the University of California, Berkeley.

**David Unwin** is currently visiting professor at the University College London Department of Geomatic Engineering. He was previously learning programmes director at U.K. eUniversities Worldwide Ltd., chair in the School of Geography at Birkbeck College, University of London, England, and pro-vice master of the college with special responsibility for communications and information technology. He was an early pioneer in the United Kingdom of the application of computing to geographic problems and to geographic education. In 1989 he was the founding director of the Computers in Teaching Initiative Centre for Geography. Over the past 25 years, he has served on various committees of the Royal Geographical Society and the Geographical Association. He is also a past council and management committee member of the Association for Geographic Information. Professor Unwin has led or co-led a number of major GI research projects. From 1989 to 1993 he was assistant director of the U.K. Economic and Social Research Council's Midland's Regional Research Laboratory at Leicester University. He has developed tools for the visualization of geographic data and for use in the development of virtual field courses. He has also developed tools for the characterization of urban surfaces in physically meaningful terms for inputs into urban climate models. He received a B.S. from the University of London (1965) and a master's degree in philosophy from the University of London (1970).

*NRC Staff*

**Ronald F. Abler** is currently a senior scientist at the National Academies and secretary general and treasurer of the International Geographical Union. He was executive director of the Association of American Geographers from 1989 through 2002 and professor of geography at The Pennsylvania State University from 1967 to 1995. From 1984 to 1988, Dr. Abler was director of the Geography and Regional Science Program at the National Science Foundation, where he coordinated the establishment in 1988 of the National Center for Geographic Information and Analysis. Dr. Abler's research explores the ways different societies have used intercommunications technologies at different times and places. He has written numerous research articles and is coauthor or editor of several books. Most recently he edited *Global Change and Local Places: Estimating, Understanding, and Reducing Greenhouse Gases*. Dr. Abler was president of the AAG (1985-1986). He has received the Centenary Medal of the Royal Scottish Geographical Society (1990), Association of American Geographers Honors (1995), the Victoria Medal of the Royal Geographical Society/Institute of British Geographers (1996), and the Samuel Finley Breese Morse Medal of the American Geographical Society (2004). He earned his B.A., M.A, and Ph.D. (1968) in geography at the University of Minnesota.

**Anthony R. de Souza**, director, Board on Earth Sciences and Resources, was previously executive director of the National Geography Standards Project, secretary general of the 27th International Geographical Union Congress, editor of *National Geographic Research & Exploration*, and editor of the *Journal of Geography*. He has held positions as a professor and as a visiting teacher and scholar at the George Washington University, University of Wisconsin-Eau Claire, University of Minnesota, University of California, Berkeley, and University of Dar es Salaam in Tanzania. He has served as a member of NRC committees. He holds B.A. (honors) and Ph.D. degrees from the University of Reading in England, and has received numerous honors and awards, including the Medalla al Benito Juarez in 1992 and the Gilbert Grosvenor honors award from the Association of American Geographers in 1996. His research interests include the processes and mechanisms of economic development and human-environment relationships. He has published several books and more than 100 articles, reports, and reviews.

**Paul M. Cutler** is a senior program officer for the Polar Research Board of the National Academies. He directs studies in the areas of polar science and atmospheric science. Before joining the Polar Research Board staff, Dr. Cutler was a senior program officer in the Academies' Board on Earth

Sciences and Resources, where he directed the Mapping Science Committee and studies in Earth science and geographic information science. Before joining the Academies, he was an assistant scientist and lecturer in the Department of Geology and Geophysics at the University of Wisconsin-Madison. His research is in glaciology, hydrology, meteorology, and quaternary science, and he has conducted fieldwork in Alaska, Antarctica, arctic Sweden, the Swiss Alps, Pakistan's Karakoram mountains, the midwestern United States, and the Canadian Rockies. Dr. Cutler received an M.Sc. in geography from the University of Toronto and a Ph.D. in geology from the University of Minnesota.

**Kristen Campbell** is the program director for the George Washington University's Africa Center for Health and Security. Previously, she was a program officer with the National Academies' Board on Earth Sciences and Resources. She received her B.A. and M.S. degrees in environmental sciences from the University of Virginia. Prior to joining the National Academies, she was director of programs at the Renewable Natural Resources Foundation (RNRF) in Bethesda, Maryland. She provided staff support for several interdisciplinary and multidisciplinary programs that assessed renewable natural resources requirements and formulated public policy alternatives. She also edited RNRF's *Renewable Resources Journal*. While at the National Academies, Mrs. Campbell worked on studies involving coal waste impoundments, geographic information for sustainable development in Africa, and the U.S. Climate Change Science Program Strategic Plan. She was also the study director for the National Academies' Geographical Sciences Committee. She is a member of the Association of American Geographers.

# Appendix B

# Workshop Agenda and Participants

## AGENDA

**Workshop on Beyond Mapping: The Challenges of New Technologies in the Geographic Information Sciences**
**The National Academies**
**Keck Center**
**500 Fifth St. NW, Room 204**
**Washington, DC 20001**
**August 22 – 23, 2002**

*Thursday, August 22, 2002*

**OPEN SESSION**

8:30 a.m. Welcome and Review of Day's Agenda
*Joel Morrison, Chair*

8:50 a.m – 12:00 p.m. **TECHNICAL VISIONARIES**

8:50 a.m. Location Based Services
*Gary D. Pulford*
Manager, Business Development-Wireless
Intrado Inc.

| | |
|---|---|
| 9:10 a.m. | Sensor Networks<br>*Deborah Estrin*<br>Professor, Computer Science Dept. & Director LECS<br>University of California |
| 9:30 a.m. | Multi-modal Interaction<br>*Sharon Oviatt*<br>Professor/Codirector<br>Center for Human-Computer Communication<br>Oregon Graduate Institute of Science & Technology |
| 9:50 a.m. | Web-based Security and Web Futures<br>*John Gage*<br>Chief Researcher<br>Sun Microsystems |
| 10:10 a.m. | Break |
| 10:30 a.m. | Grid Computing<br>*Chaitan Baru*<br>California Institute for Telecommunications & Information Technology |
| 10:50 a.m. | Augmented Reality<br>*Steve Feiner*<br>Computer Graphics & User Interfaces Laboratory<br>Columbia University |
| 11:10 a.m. | Speakers gather for questions and answers |
| 12:10 p.m. | Lunch in meeting room |
| 1:20 – 4:00 p.m. | **EARLY ADOPTERS** |
| 1:20 p.m. | Insurance Services Office<br>*Bill Raichle*<br>Assistant Vice President |
| 1:40 p.m. | U.K. Ordnance Survey<br>*Duncan Sheill*<br>Director of Strategy |

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|---|---|
| 2:00 p.m. | Break |
| 2:20 p.m. | International Telco<br>*Barry Glick*<br>Chairman, Webraska |
| 2:40 p.m. | Field Computing<br>*Michael Goodchild*<br>University of California, Santa Barbara |
| 3:00 p.m. | Speakers gather for questions and answers |
| 4:00 p.m. | CONCLUSION OF PANEL SESSIONS |
| 4:00 p.m. | NASA<br>*Ron Birk*<br>Director, Earth Science Applications Division |
| 4:30 | Adjourn and Reception |

*Friday, August 23, 2002*

**CLOSED SESSION**

8:00 a.m. – 4:30 p.m.

## PARTICIPANTS

**Chaitan Baru**, California Institute for Telecommunications & Information Technology, San Diego, California
**Ron Birk**, Earth Science Applications Division, NASA, Washington, D.C.
**Deborah Estrin**, Computer Science Deptartment & Director LECS, University of California, Los Angeles
**Steve Feiner**, Computer Graphics & User Interfaces Laboratory, Columbia University, New York
**John Gage**, Sun Microsystems, Santa Clara, California
**Barry Glick**, Webraska, Washington, D.C.
**Michael Goodchild**, University of California, Santa Barbara
**Sharon Oviatt**, Center for Human-Computer Communication, Oregon Graduate Institute of Science & Technology, Beaverton
**Gary D. Pulford**, Business Development - Wireless, Intrado Inc., Longmont, Colorado
**Bill Raichle**, Insurance Services Office, New York
**Duncan Shiell**, U.K. Ordnance Survey, Southampton

# Appendix C

# Evolution of the Mapping Sciences

## THE NEED FOR MAPS AND THE MAPPING SCIENCES

Human senses provide only limited means for observing and remembering our surroundings. At any instant, an individual can see little more than a millionth of the Earth's surface if standing upon it. To know more than this requires the sharing and compiling of experience, and the development of tools for mapping, reproducing, and distributing mapped information—processes formalized and systematized in the classic Greek era by Eratosthenes (276-194 BCE), Ptolemy (AD 85-165) and others. In the early modern period in the West, Portuguese navigators dominated exploration of the wider world owing to the school of mapping and navigation established by Prince Henry ("The Navigator") of Portugal (1394-1460) at Sagres in the early fifteenth century (Ure, 1977). After regular European contact with the Americas at the end of that century, the mapping sciences evolved rapidly, driven by European commercial and imperial ambitions and accompanying warfare (Black, 1997). Maps and mapping became valuable enough to spur governments to devote substantial resources to developing the tools needed to solve specific mapping and navigational problems, such as the accurate determination of longitude (Sobel, 1995).[1]

The history of science is full of examples of the vital role that tools have played in advancing human understanding. Galileo's work de-

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[1] A timeline of selected events in the history of the mapping sciences is appended to this appendix (Table C-1).

pended on his acquisition and further development of telescopes; today our understanding of the cosmos is advancing rapidly thanks in part to the Hubble space telescope. The invention of the microscope, the digital computer, and even the camera are all significant milestones in the history of science. In numerous instances, the complexity of new tools fostered new disciplines devoted primarily to advancing the tools, while contributing only indirectly to advancing science through the application of the tools. For example, the analysis of x-ray diffraction images is sufficiently difficult and its results of sufficient importance in mineralogy and molecular biology that x-ray crystallography has become a recognized scientific discipline. Similar histories characterize microscopy, statistics, the computer sciences, and mapping. In the same way, new mapping disciplines emerged following significant technological advances. For example, the emergence of photogrammetry in the twentieth century depended on the invention of the photograph and the airplane. Other disciplines emerged as a result of strategic need, and the massive government investment that followed. For example, geodesy, the science of accurate measurement of Earth, was transformed as a result of the ballistic missile programs of the 1950s.

Rarely does a change in tools result in a true revolution, and the mapping sciences are now experiencing only the second such revolution in over five millennia of collective history. The first true revolution was in response to the invention and dissemination of printing. The second is based on the invention and application of digital electronic technology to the mapping sciences. Prior to printing, every map was a unique hand-drawn manuscript. With printing came the need to standardize mapping conventions and practices, in order to satisfy the larger market for maps that printing itself created. Similarly, digital technology has forced comprehensive rethinking of almost all aspects of the mapping sciences during the last 30 years. In addition to making a large number of maps and map-like illustrations even more widely available than did printing, digital technology offers the further capabilities of producing highly customized maps tailored to each individual user's individual specifications, and of permitting each individual to personally produce such customized maps. In a very short period of time, the mapping sciences have shifted focus from producing multiple copies of identical maps expected to satisfy a variety of purposes to today's emphasis on specialized location-based information products and services synthesized on demand.

## The Mapping Sciences in 1975

Of the three major mapping science sectors (academic, government, and private), federal governments traditionally exercised dominant leadership in creating, sponsoring, and implementing technological innovations in the mapping sector, abroad as well as in the United States. Agencies in the Departments of Defense, Commerce, and Interior had large budgets and incentives to fund improvements in mapping technologies, leading innovators to try to satisfy agency needs. Private firms involved in the mapping sciences, commercial map publishers, and small surveying firms lagged in accepting and employing new developments. Academic mapping scientists experimented continuously, but focused primarily on developing and updating courses that met the needs for professionals trained to use the evolving technologies employed by federal agencies. Most courses were offered by individual academic departments, with little or no coordination across department lines. Cartography, geodesy, and photogrammetry were taught respectively in departments of geography, geodesy, and civil engineering or forestry. Some surveying was taught in civil engineering programs, but much was taught in junior or community colleges or on the job. Remote sensing courses were taught in geography or civil engineering.

## The Mapping Sciences in 2005

A short 30 years later, the widespread adoption of digital technology has forced rapid change with no clear diminution in sight. In 2005, private industry, using digital technology and meeting an increasingly wide array of user demands and expectations, leads in developing and implementing digital technology and in providing location-based services. Government agencies have undergone massive changes and are still groping to understand their places in a new technological world. Most have come to realize that they are now primarily spatial-data analysts, archivists, and users and no longer data collectors and map producers. In 1975, the costs and the intricacies of the latest mapping science technologies were cost prohibitive for almost all organizations except the federal government, making it necessary for the federal agencies to be data collectors as well as mappers. Now government agencies at all levels, including some that never had or needed spatial data, have become spatial-data providers, users, and integrators.

This rising importance of local and state government agencies relative to federal agencies is one of the most profound outcomes of the digital revolution. The data accuracy and precision demanded by today's larger array of users requires that data collection be done at local levels in forms and formats acceptable to national users. Thousands of local governments are now engaged in the collection, processing, analysis, archiving, and visualization of highly precise and accurate geographic data, tasks for which tens of thousands of GIS/GIScience professionals are needed. In recent years the annual user conference of the leading GIS software vendor has drawn 10,000 to 12,000 participants, in contrast to the 2,000 or so who attended meetings of the relevant professional organizations in the 1970s.

In some respects, the academic sector has been the slowest to effect permanent changes in response to the digital revolution. Educational programs are often deeply disciplinary in nature. Training is still done in individual departments, each focusing only on part of the total mapping science picture. Within academia, confusion persists regarding the ways the scientific, engineering, and application components of GIS/GIScience relate to each other and to traditional disciplines. In response to the strong demand for trained GIS/GIScience professionals, many programs have introduced coursework that stresses software manipulation skills at the expense of the conceptual depth needed to accommodate rapid and continuing scientific and technological change. The capacity to meet the greatly increased need for trained GIS/GIScience trained professionals has not been put in place, leading to the worrisome prospect of thousands of individuals using GIS software to produce analyses and visualizations based on assumptions and techniques they do not fully understand.

## Core Mapping Disciplines

The set of disciplines relevant to the mapping sciences has expanded in the last 30 years as a result of four developments: increased availability of affordable digital technology and data, a heightened appreciation for the analytical power of geospatial tools, increased locational accuracy and precision of data owing to the deployment of the Global Positioning System (GPS), and increased awareness of the value of the spatial data on the part of entrepreneurs and society.

## Influences of Information Technology

Information technology, particularly digital technology, has strongly affected the core mapping sciences. Cartography has benefited from the power of computers to support rapid editing and composition of maps in ways directly analogous to the ways computers have enhanced the composition and editing of text. Today virtually all mapmaking is done on-screen rather than on paper, although the eventual product may appear almost identical to paper maps made long before the invention of computers.

But computers have also wreaked profound and far-reaching changes on the society that ultimately defines the need for maps and the uses to which they are put. Mapmaking originated as a solution to the basic need to share geospatial information. The practice of printing and disseminating large sheets with symbolic representations of Earth's surface was one solution to that need, optimized for the technology of the time. Today not all ways of sharing information require dissemination on paper. The traditional role of the newspaper, for example, has been partially eclipsed by television, radio, and the Internet. Roles that mass-produced paper maps once performed, such as providing the information needed to navigate the street network of an unfamiliar city, are now being performed by such online information resources as MapQuest.com, which provides customized driving directions to millions of users per day, as well as printable maps. Some new tools enhance and augment the traditional roles of maps, while others replace them.

To understand the impact of information technology on the mapping sciences, one must understand the role of geospatial information in society generally. How geospatial information is acquired and used will depend on particular applications; information may be delivered in the form of a paper map, but it may also be transmitted through an online service to a user's printer. Since the advent of information technology, particularly the Internet, the tools and services available to support geospatial information applications have expanded, and geospatial information is now used in a host of ways that were almost inconceivable three decades ago. Many of these uses are associated with time-dependent transactions, in sharp contrast to traditional mapping's emphasis on the relatively static features of Earth's surface. For example, every credit card transaction generates a record that is located in time and space.

There have been many studies of the impact of digital technology on mapping and the potential of such new digital technologies as GIS (for example, NRC, 1997). The tools of mapping now extend far beyond those that provided the initial impetus for the core disciplines of cartography, geodesy, surveying, photogrammetry, and remote sensing; and their impacts on mapping generally will be far greater than their specific impacts on the core disciplines.

As Prince Henry staffed his school at Sagres with specialists in the mapping technology of the time, so the national mapping agencies that evolved in the nineteenth and twentieth centuries and their state and private-sector equivalents drew personnel from the core disciplines of the mapping sciences. Today, traditional national mapping agencies face unprecedented challenges as they struggle to evolve in an era of very rapid technological change. How, for example, should these agencies respond to the potential of location-based services, the umbrella term for services that provide information based on the current location of the user, through mobile phones and other portable devices? Who should today's Prince

Henry recruit to the modern equivalent of his school? And how should such people be trained to be most effective in addressing these questions?

Although the four core mapping sciences—cartography, geodesy, photogrammetry and remote sensing, and surveying—are to some degree independent, they share strong commonalities, including a focus on the common objective of mapping. Today, however, a surveying specialist is expected to be familiar with aspects of information technology, particularly GIS, GPS, and image processing, and possibly the science behind information technology. Surveyors are also expected to know aspects of statistics, and particularly error analysis and adjustment theory. The curriculum of surveying programs has had to expand in recent years, with all that implies in terms of excessive demands and information overload. Mapping agencies clearly face difficult human resource issues in the coming decade that can only be addressed with a clear vision of the new nature of mapping, geospatial information, and their core disciplines.

## Adding Disciplines to the Mapping Sciences

Five disciplines are particularly relevant to today's mapping sciences. Each is an established enterprise in its own right, with a domain that overlaps strongly with mapping:

### *Computer Science*

Computer scientists study fundamental issues related to digital computing, including its data structures, algorithms, and indexing schemes. They address the design of operating systems, programming languages, and database management systems. Computer scientists' interests also extend to the principles underlying interactions between humans and computers, and the effects of computing on society. Particularly relevant to mapping are such computer science specialties as computational geometry, object-oriented database management, spatial databases, and computer graphics. Conferences in these specialties tend to attract mapping specialists, and computer scientists in these specialties commonly attend meetings organized by the mapping sciences. A study by the NRC's Computer Science and Telecommunications Board examined research needs in specialties relevant to the mapping (NRC, 2003a).

### *Information Science*

Geospatial information is a particularly well-defined subset of information, and it has consequently attracted the attention of information scientists interested in the fundamental nature of information and its underlying principles. Information science has strong roots in library science, and libraries of geospatial information have become a focus of research in the digital library community (e.g., the Alexandria Digital Library Project). In particular, information science provides the framework for research on metadata, cataloging systems, interoperability among archives, and automated search over distributed archives, all of which are important to the mapping sciences given their interest in information sharing.

### *Electrical and Computer Engineering*

Because of their potential roles in the inexpensive production of geospatial information from remotely sensed images, image processing and pattern recognition are important technologies for mapping. For this reason, the military and intelligence communities have invested heavily in electrical engineering research over the past four decades. Given the vast volumes of data that are typical of remote sensing, electrical engineering also contributes to mapping science through its interest in data compression.

### *Cognitive Science*

Cognitive scientists study the acquisition and development of mental abilities and their use in daily activities. As the mapping sciences have been affected by information technology, such topics have become increasingly important for two reasons. First, as geospatial information becomes more pervasive, it is essential that information be made widely available, including to the young, whose cognitive skills may not be fully developed, and to the disabled, particularly the visually impaired. Second, interaction between humans and computers often must occur in such constrained circumstances as in vehicles while driving, where it is essential that information be presented in ways that are readily understood. In recent years, there has been productive interaction between the mapping and cognitive science communities.

### *Statistics*

Because geospatial information is an approximation toward the real world, its users inevitably face uncertainty when using it to solve real problems. A GPS receiver will yield only an approximate measurement of position, for example, and a map of land use can only give an approximate indication of actual conditions on the ground. Specialists in geostatistics and spatial statistics are interested in mapping as an application realm for statistical theory, and in recent years several conferences on spatial-data uncertainty have drawn mapping scientists and statisticians. Substantial advances have been made in the description and study of error and uncertainty in geospatial information, its propagation through the manipulations that occur in GIS, and in its visualization (Zhang and Goodchild, 2002).

The set of core disciplines needed for robust mapping science has grown substantially in the last 30 years. To specialists in these additional disciplines, the mapping sciences are often seen as offering intriguing or unusual applications rather than as an essential parts of the discipline's core. This focus on an application is always risky for a researcher whose priority is advancing the parent discipline—it is too often seen as marginal and less meritorious than core research. Accordingly, researchers pursuing such interests run the risk of being seen as marginal within their own disciplines. Even so, spatial specialties within these relevant disciplines have emerged, often identified with the adjective "spatial," as in spatial databases, spatial statistics, and spatial cognition. However sound the basis for the mapping sciences as an application topics for these five disciplines, or even as the basis of an important specialty, the tradition of dividing the scientific community along well-established disciplinary lines remains a strong conservative influence.

## Geographic Information Science

By 1991, it was evident that the cumulative force of new technologies and the engagement of new disciplines were producing a creative tension in the mapping sciences. Profound structural changes were under way not only in the agencies primarily concerned with the production of maps but also among the country's academic disciplines. Programs were being reorganized to recognize both the new skills needed by mapping scientists and the new commonalities between them. One of the most conspicuous results of this tension was an attempt to rename some of the components of mapping science. Two new terms emerged: "geomatics," constructed from "informatics" and implying a mapping science heavily dominated by information technology, and "geographic information science" (GIScience). In proposing the latter term to describe a new field addressing the fundamental issues of geospatial information, Goodchild (1992) intended to imply a strong link to GIS, and to play on the ability of GIS to attract widespread attention.

Many surveying departments redefined themselves at this time, and became departments of geomatics or geomatics engineering. The University Consortium for Geographic Information Science (UCGIS) was founded in 1996 as a consortium of U.S. research universities (http://

www.ucgis.org [accessed May 24, 2006]). Several journals changed their titles: *The American Cartographer* became *Cartography and Geographic Information Science*, and the *International Journal of GIS* became the *International Journal of GIScience*. A series of biennial international conferences in GIScience began in Savannah, Georgia, in 2000, and a number of more established but smaller conferences now address specific aspects of GIScience.[2]

Since 1995, "GIScience" has come to have two distinct meanings, one referring to the use of GIS in scientific applications and the other addressing the fundamental research principles on which GIS is based. In 1996, UCGIS recognized the wider import of the latter meaning by developing a 10-point research agenda (UCGIS, 1996), which attests to the breadth of this emerging discipline and the complexity of geospatial technology. Although subsequently augmented, its 10 research focuses remain a useful guide to the content and academic context of GIScience:

1. Spatial data acquisition and integration;
2. Distributed computing;
3. Extensions to geographic representations;
4. Cognition of geographic information;
5. Interoperability of geographic information;
6. Scale;
7. Spatial analysis in a GIS environment;
8. The future of the spatial information infrastructure;
9. Uncertainty in geographic information and GIS-based analyses; and
10. GIS and society.

Both "geomatics" and "GIScience" were coined in response to a perceived need to reshape the academic landscape of the mapping sciences. Their adoption signals a more holistic view of the mapping sciences and the need to integrate content from the disciplines that have recently joined the mapping science community. The terms carry somewhat distinct connotations: "Geomatics" is more strongly associated with engineering and the surveying tradition, whereas "GIScience" is more strongly associated with geography, information sciences, and computer science. In Canada, geomatics is the dominant term and the focus of government policy.

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[2] For a history of GIScience, see Mark (2003), and for explorations of its epistemological significance see Wright et al. (1997).

## Governments

In 2001, the U.S. Office of Management and Budget (OMB) initiated Geospatial One-Stop, one of a series of interagency, multigovernment e-government activities (Sidebar 1-2) designed to help users find geospatial data. OMB has more recently asked federal agencies that are required to have in place Enterprise Architecture plans for managing information to consider development of a "geospatial profile" for enterprise architecture planning. A "Geospatial Enterprise Architecture" (GEA) Working Group is being formed under the auspices of the federal CIO Council Architecture and Infrastructure Committee (AIC) and the FGDC. This group, while conducting some meetings in person, is taking advantage of communications technologies by using a wiki (a collaborative website set up to allow user editing and adding of content) as its primary way to interact and share documents. (Sidebar C-1 and http://colab.cim3.net/cgi-bin/wiki.pl?GeoSpatialCommunityofPractice [accessed 25 April 2006]). The GEA Working Group was not initiated by geospatial experts, but at the behest of the general information technology community, which saw a need to more effectively integrate geospatial considerations into high-level agency information management efforts.

At the state level, most states have formed some sort of coordinating council that facilitates the exchange of knowledge among state agencies regarding geospatial data and activities (http://www.nsgic.org/ [accessed 24 May 2006]). These developments follow the establishment in the early 1990s of the National States Geographic Information Council (NSGIC) to provide a forum on GIS/GIScience for communications among the states. Today other levels of government, as well as academics and private-sector representatives participate in NSGIC meetings.

## The Private Sector

The same drivers of change that spurred action in the academic and government sectors have significantly affected the private sector. It has expanded from a handful of small, highly specialized firms 30 years ago to hundreds of enterprises (some of them large) today. Early innovators of GIS software focused on using aerial photographs and producing touring maps and atlases. Today firms range from software developers to consultants and data providers, from producers of airborne digital orthophotographs to aerospace corporations deploying high-resolution Earth-observing satellites, and from local firms creating vector-based recreation maps to national data vector collection firms (e.g., Navigation Technologies or NAVTEC, Teleatlas, Geographic Data Technology). The growth of this industry is a direct result of the pervasiveness of mapping tools

## SIDEBAR C-1
## The Geospatial Enterprise Community of Practice

**Objectives**

- To establish an inclusive community of practice in order to consistently integrate and promote geospatial concepts in the context of enterprise architecture practices;
- To develop a Geospatial Profile guidance document for the Federal Enterprise Architecture and companion documentation for program-level implementers; and
- To conduct outreach activities and demonstrations to highlight the application of Profile guidance in operational, multijurisdictional settings.

**Roles and Responsibilities**

The Geospatial Community of Practice / GEA Technical Working Group has representatives from federal, state, local government, and industry. Participating organizations are committed to providing information and personnel resources integral to the initiative. The FGDC Secretariat and the AIC provides project support, guidance, and contractor support. Contractor support includes document interpretation and preparation, meeting synopses, collaborative workspace management and updates, and interaction with the commercial sector. See draft charter for additional information.

SOURCE: http://colab.cim3.net/cgi-bin/wiki.pl?GeoSpatialCommunityofPractice. Accessed 25 April 2006.

that have led to increasing demand for location-based information and more tools.

The private sector has created industry associations not only to promote sharing of information but also to lobby Congress and state and local governments for various causes, including increased federal funding to the private sector as contracts (e.g., Management Association for Private Photogrammetric Surveyors) and for enhancing funding for geospatial activities overall (e.g., Spatial Technology Industry Association). One of the most visible private-sector organizations that has significantly broadened its membership over the last few years, is the Open GIS

Consortium (OGC)[3] (Sidebar S-3). The OGC promotes open standards[4] for the GIS industry and has garnered worldwide support for its agenda from governments, academia, and the private sector.

Other organizations, such as the ISO (International Organization for Standards) (which considers geospatial metadata standards) and the World Wide Web Consortium (W3C), also focus on standards, but from a broader perspective. W3C develops interoperable technologies (specifications, guidelines, software, and tools) to develop the Web to its fullest potential (http://www.w3.org/ [accessed 24 May 2006]).[5] ISO covers standards relating to everything from screws to practices for environmental regulations (http://www.iso.org/iso/en/ISOOnline.frontpage [accessed 24 May 2006]). ISO's work relevant to GIS/GIScience has focused on preliminary aspects of international standards for GIS and for location-based services.

## The Nonprofit Sector

As GIScience has spread throughout the public and private sectors, it has also engaged the interest of the nonprofit sector. The three organizations just mentioned (MAPPS, STIA, and OGC) are all not-for-profit organizations, with varying abilities and inclination to lobby Congress and other governments for funding to support geospatial activities. Other nonprofits include professional societies with specific interests in geospatial data and technology (Association of American Geographers, American Congress on Surveying and Mapping, American Society for Photogrammetry and Remote Sensing, Geospatial Information and Technology Association, and the Urban and Regional Information Systems Association). Their conferences and journals often provide a means for many sectors and disciplines to collaborate and interact on issues of com-

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[3] OGC trademarked the phrase "OpenGIS" in 28 countries to enable the consortium to position itself and its products (e.g., OpenGIS Specifications) as truly open and vendor neutral.

[4] Open interfaces and protocols defined by OpenGIS® Specifications support interoperable solutions that "geoenable" (create standards for interoperability that will advance the use of geospatial data) the Web, wireless- and location-based services, and mainstream information technology, and empower technology developers to make spatial information and services accessible to different applications.

[5] W3C members consist of private technology companies, nonprofit organizations, coalitions, academic institutions, and government agencies interested in working "together to design Web technologies that build upon its universality, giving the world the power to enhance communication and commerce for anyone, anywhere, anytime and using any device" (http://www.w3.org/Consortium/Member/List).

mon interest. For example, URISA was formed after the 1960 U.S. census, when researchers recognized the potential to develop maps from newly available digital census data and to use GIS to analyze urban and regional issues. It carries out its mission through vendor-neutral workshops and publications.

**TABLE C-1** Timeline of Selected Events in the History of the Mapping Sciences in the U.S.

| Date | Event |
|---|---|
| 1790 | The first census was taken, under the responsibility of Secretary of State Thomas Jefferson. That census, taken by U.S. marshals on horseback, counted 3.9 million inhabitants. |
| 1807 | U.S. Coast and Geodetic Survey established to provide better charts of coastal waters and navigational aids for commercial interests. (They did not begin work until 1812 and shortly thereafter became part of the navy.) |
| 1810 | The census was expanded to obtain information on the manufacturing, quantity, and value of products. |
| 1820 | New York state funds development of a geological survey to improve agriculture in Albany County. |
| 1823 | North Carolina General Assembly authorizes creation of a statewide geological survey. |
| 1824 | Congress authorizes army engineers to make engineering surveys for roads and canals for national military, commercial, or postal purposes. |
| Early 1830s | Several eastern and central states establish state geological surveys. |
| 1834 | Topographical Bureau of the U.S. Army is authorized by Congress to conduct geological investigations to construct a geological map of the United States. |
| 1835 | Geological Survey of Great Britain is established. |
| 1840 | The census adds questions on fisheries. |
| 1848 | U.S. Interior Department is established including the General Land Office, the Pension Office, the Office of Indian Affairs, and the Census. |
| 1850 | The census added data on taxation, churches, pauperism, and crime. |
| 1850 | George T. Hope is generally credited with having fostered the idea of specialized and detailed fire insurance maps in the United States. Around 1850 Hope, who was at the time secretary of the Jefferson Insurance Company, began to compile a large-scale map of a portion of New York City for use in calculating fire risks. This effort became part of Sanborn. |
| 1853 | Congress charges the U.S. Army topographical engineers to conduct surveys to determine the best railroad route from the Mississippi River to the Pacific Ocean. |
| 1860 | California legislature establishes a state geologic survey (the only state geological survey that will survive the Civil War). |
| 1867 | Congress authorizes surveys of the West for geology and natural resources along the 40th parallel under the U.S. Army Corps of Engineers, and a geological survey of the State of Nebraska under the Interior General Land Office. |
| 1867 | The Sanborn Map Company, primary American publisher of fire insurance maps was established (http://www.lib.utah.edu/digital/sanborn/browse.html [accessed 24 May 2006]). |

**TABLE C-1** Continued

| Date | Event |
|---|---|
| 1869 | First Rand McNally map published: *The Western Railway Guide.* |
| 1870 | National Weather Service (originally called the Division of Telegrams and Reports for the Benefit of Commerce) established under the secretary of war. |
| 1878 | U.S. Geological Survey established with a $100,000 budget and 38 employees. |
| 1883 | Sanborn appears to have begun systematic registering of maps, with deposit copies. The sheets carrying the 1883 date are the earliest in the Library of Congress. D. A. Sanborn dies in 1883. |
| 1886 | Dr. Herbert Hollerith conducts the first practical test of his "tabulating machine" in recording vital statistics for the Baltimore Department of Health. He patents this machine in 1889. |
| 1888 | The National Geographic Society is established. |
| 1890 | Dr. Herbert Hollerith's (a Census Bureau statistician) punched-card tabulating machines are used for tabulating census data. The machines use an electric current to sense holes in punched cards to keep a running total of data. Sixty-three million people counted. |
| 1896 | Dr. Herman Hollerith, son of a German immigrant and Census Bureau statistician forms the Tabulating Machine Company. |
| 1899 | Sanborn Map Company acquired Perris and Browne firm, and the name is changed to Sanborn Perris Map Company Ltd. until in 1902 the name was shortened to the Sanborn Map Company. |
| 1902 | The Census Bureau becomes a permanent institution by an act of Congress. |
| 1902 | American Automobile Association formed in Chicago. |
| 1904 | Rand McNally extends its transportation business to include motorcars and published the *New Automobile Road Map of New York City & Vicinity*, the first of its kind. |
| 1904 | Association of American Geographers is established. |
| 1909 | L. P. Lowe, president of the California State Automobile Association (CSAA) proclaims that "California is the first state in the Union to produce a comprehensible, reliable highway map." The map, which showed the "major" highways of California and Nevada, was sent without charge to all members, launching CSAA's renowned cartographic business. |
| 1910 | B. F. Goodrich, the nation's most prominent tire company, produced the first of its series of road-sign route books. This required the placing of "guide posts" from coast to coast, each bearing distance and directional information beneath the Goodrich logo. This system served the automobilist through the decade until the free, folding-type oil company road maps became readily available. The strip map lingered on, however, as it led the driver past the businesses of the sponsors. |
| 1910 | International Society for Photogrammetry and Remote Sensing is established. |

*continued*

**TABLE C-1** Continued

| Date | Event |
|---|---|
| 1911 | IBM incorporated in the State of New York as the "Computing-Tabulating-Recording Company, C-T-R. (The name is changed to IBM in 1924). One of the major companies that becomes part of C-T-R is Herbert Hollerith's Tabulating Machine Company. |
| 1917 | Randy McNally implemented a road-numbering system for Illinois that is still used today (including Route 66). |
| 1924 | The National Conference on Street and Highway Safety, whose chairman was the Secretary of Commerce Herbert Hoover, authorized a committee to draft a uniform motor vehicle code for all 48 states. Two years later, the laws were presented and adopted by the second conference. The individual states did not move so quickly, and some adopted the package in their own time, but a standardized code of laws was a major achievement of effective nationwide traffic regulations. |
| 1924-1925 | By the 1920s, commercial publishers such as Rand McNally had begun to produce the modern road atlas. The first was published in 1924 (or 1925) and was called "The Rand McNally Auto Chum." Hammond and Gallup produced their own road atlases, each with its own identifiable characteristics. Clason offered an atlas featuring spectacular cover graphics that seemed particularly suited to the West. Jenney issued a free eastern equivalent with covers in art deco style. |
| 1934 | American Society for Photogrammetry and Remote Sensing is established. |
| 1939 | Within 24 hours of Germany's invasion of Poland in 1939, Rand McNally was publishing escape maps for aviators, illustrating underground safehouses. Producing these maps on vegetable parchment enabled captured pilots to eat the maps instead of allowing them to fall into the hands of the enemy. |
| 1941 | American Congress on Surveying and Mapping is established. |
| 1953 | OMB issues Circular A-16 to encourage coordinated federal mapping and surveying efforts. |
| 1957 | Sputnik, U-2 high-altitude photography for mapping. |
| 1960 | William (Bell) Fetter of Boeing coins the term "computer graphics" to describe the work he is doing in analyzing human factors in cockpit drawings. |
| 1961 | Dr. Edgar Horwood at the University of Washington receives tapes of census data. At the time there was no mechanism for disseminating digital census data (the tapes were an "internal artifact" of the census). |
| 1962 | Horwood, Hugh Calkins, and others conduct two-week training classes in use of census data and computer mapping (origin of URISA). |
| 1963 | Roger Tomlinson uses the phrase "geographic information system" as part of the Canadian Land Inventory, which is subsequently called CGIS. |

**TABLE C-1** Continued

| Date | Event |
|---|---|
| 1963 | Forty eight people meet in Los Angeles for first URISA gathering. Mayor Yorty's office gives keynote indicating commitment to incorporating information systems and computers into public administration process. |
| 1963 | Howard Fischer is developing prototypes of SYMAP (Synagraphic Mapping System) at Northwestern University (related to census tape use). |
| 1964 | GPS specifications are developed by the Department of Defense. |
| 1964 | One hundred seventy five people meet at the University of Pittsburgh (as "second annual" URISA meeting). Ad hoc committee created to formalize the organization. |
| 1964 | Howard Fischer starts the Harvard Laboratory for Computer Graphics and Spatial Analysis and continues work on SYMAP. |
| 1966 | SYMAP is "released." |
| 1967 | OMB revises Circular A-16 to outline mapping responsibilities of the Departments of the Interior, Commerce, and State. |
| 1967 | DIME (Dual Incidence Matrix Encoding, and later Dual Independent Map Encoding) file format is developed by Census Bureau staff working with the Harvard Graphics Lab and the New Haven Census Study. |
| 1969 | ESRI is established by Jack and Laura Dangermond. |
| 1969 | M&S Computing (later renamed Intergraph) started by Jim Meadlock and four others. |
| 1969 | First spatial-data transfer standard published by Experimental Cartography Unit. |
| 1971 | Defense Mapping Agency is created. |
| 1972 | NASA launches ERTS-1 (Landsat-1) (operations terminate in 1978). |
| 1973 | State of Maryland (John Antenucci) initiates effort to create a statewide GIS (Maryland Automated Geographic Information System) working with ESRI. |
| 1973 | U.K. Ordnance Survey started digitizing maps. |
| 1973 | Federal Mapping Task Force issues its report. |
| 1974 | USGS started digitizing land use and land cover maps (Geographic Information Retrieval and Analysis). |
| 1975 | NASA launches Landsat-2 (operations terminate in 1981). |
| 1976-1977 | USGS pilots and starts producing digital elevation models (DEM) and digital line graphs (DLG) from its traditional paper products. The concept of the National Digital Cartographic Data Base is adopted in 1977. |
| 1978 | NASA launches Landsat-3 (operations terminate in 1983). |
| 1979-1981 | Carter and Reagan initiate and accelerate process of Landsat commercialization. |
| 1980 | NRC Multipurpose Cadastre Report published. |
| 1980 | Federal Emergency Management Agency integration of USGS 1:2 million maps. |

continued

**TABLE C-1** Continued

| Date | Event |
|---|---|
| 1981 | FICCDC (Federal Interagency Coordinating Committee on Digital Cartography) is formed. |
| 1982 | Automated Mapping/Facilities Mapping (AM/FM) established. Name later changed to GITA (Geospatial Information and Technology Association). |
| 1982 | NASA launches Landsat-4 Thematic Mapper data (operations limited as of 1992). |
| 1983 | Etak Inc. is formed. |
| 1984 | NASA launches Landsat-5 (still operational). |
| 1985 | First GPS satellites launched. |
| 1986 | First GIS/LIS (land information systems) Conference (sponsored by ASPRS) (meetings continue through 1996, primarily cosponsored by AAG, ASPRS, ACSM, AM/FM-GITA, URISA). |
| 1987 | Mapping Science Committee formed. |
| 1988 | NCGIA (National Center for Geographic Information and Analysis) funded by National Science Foundation. |
| 1990 | Circular A-16 revised to include geographically referenced computer readable (digital) data and to form the Federal Geographic Data Committee (FGDC). |
| 1991 | USGS topographic map series is completed. |
| 1992 | NSGIC (National States Geographic Information Council ) is formed. |
| 1992 | OMB Circular A-130 is issued. |
| 1993 | NRC report *Toward a Coordinated Spatial Data Infrastructure for the Nation* is issued. |
| 1993 | NASA launches Landsat-6 (satellite fails to orbit). |
| 1994 | Space Imaging is established. |
| 1994 | Open GIS Consortium is established. |
| 1994 | ISO Technical Committee 211 is established. |
| 1994 | Executive Order 12906 for developing the National Spatial Data Infrastructure is signed by President Clinton. |
| 1995 | FGDC clearinghouse is established. |
| 1995 | FGDC metadata standard is established. |
| 1995 | MapInfo Professional Software is available. |
| 1996 | OGIS Specification V1 is established. |
| 1999 | Space Imaging's IKONOS satellite is launched. |
| 1999 | NASA launches Landsat-7 (data anomalies May 2003). |
| 2002 | Circular A-16 is revised to clearly define FGDC and NSDI efforts. |
| 2002 | Geospatial One-Stop e-government initiative is established. |

# Appendix D

# Acronyms

| | |
|---|---|
| AIC | Architecture and Infrastructure Committee |
| ASPRS | American Society for Photogrammetry and Remote Sensing |
| CEGIS | Center for Environmental and Geographic Information Services |
| COTS | commercial off-the-shelf |
| ERTICO | Intelligent Transport Systems and Services—Europe |
| ESRI | Environmental Systems Research Institute |
| FDA | U.S. Food and Drug Administration |
| FGDC | Federal Geographic Data Committee |
| FICCDC | Federal Interagency Coordinating Committee on Digital Cartography |
| GEA | geospatial enterprise architecture |
| GIO | Geospatial Information Office |
| GIS | geographic information systems (often geographic*al* information systems in the U.K. and former commonwealth countries) |
| GISCI | GIS Certification Institute |
| GIScience | geographic information science |
| GI S&T | geographic information science and technology |
| GMS | geographic management systems |

| | |
|---|---|
| GPS | Global Positioning System |
| GWDC | Geospatial Workforce Development Center |
| MAPPS | Management Association for Private Photogrammetric Surveyors |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NCGIA | National Center for Geographic Information and Analysis |
| NGA | National Geospatial-Intelligence Agency |
| NITLE | National Institute for Technology and Liberal Education |
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | National Research Council |
| NSDI | National Spatial Data Infrastructure |
| NSF | National Science Foundation |
| NSGIC | National States Geographic Information Council |
| OGC | Open Geospatial Consortium |
| OMB | Office of Management and Budget |
| PDUFA | Prescription Drug User Fee Act |
| SDI | spatial data infrastructure |
| STIA | Spatial Technology Industry Association |
| UCAR | University Corporation for Atmospheric Research |
| UCGIS | University Consortium for Geographic Information Science |
| USGS | U.S. Geological Survey |
| W3C | World Wide Web Consortium |