Geographic Information Science: Critical Issues in an Emerging Cross-Disciplinary Research Domain

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Executive Summary

Scenarios for geographic information use in the year 2010 suggest great potential to extend the capabilities of scientific researchers, decision-makers, and the public. This potential, however, will only be realized if there are substantial advances in Geographic Information Science, enhancing knowledge of geographic concepts and their computational implementations. To assess the needs for basic research in this emerging science and technology field, a workshop was held at the National Science Foundation January 14-15, 1999. Workshop participants represented a broad range of the disciplines involved in Geographic Information Science and technology. The workshop identified two important research streams: research in basic Geographic Information Science (hereafter, GIScience), and research using geographic information *systems* (hereafter, GIS). It is imperative that research in these two areas be integrated, as applications motivate the science, and awareness of theory improves applications. Basic research in GIScience has several compelling components. First is software integration, a general problem that needs specific research to solve its geospatial dimensions. Second, scale and resolution are spatial problems that interact with the scales (characteristic lengths) of environmental and social processes and with data quality. Third, process models are a general computing problem, but again geographic applications will require uniquely geographic solutions. And fourth, usability of systems and technologies is also a major component in need of research. In addition, uncertainty and spatial dependence were recognized as important crosscutting research themes. GIScience is clearly a coherent research field of strategic importance.

Workshop participants agreed that there is an urgent need for a focused investment in GIScience, and that the National Science Foundation is the most appropriate U.S. agency to do this. Such an investment is consistent with several important national trends, represented by the President's Information Technology Advisory Committee (PITAC) report, the Administration's FY 2000 Information Technology for the Twenty-First Century (IT^2) initiative, and the National Spatial Data Infrastructure. The workshop found that there is a coherent research community poised to make advances in GIScience if sufficient research support is made available.

The workshop participants made the following recommendations to the National Science Foundation:

1. The National Science Foundation should recognize the importance of GIScience as a coherent research field, and should focus a funding activity in this area as soon as possible.
2. Both basic GIScience, and research using GIS, should be supported from the new activity, to promote the integration of these research areas.
3. The Foundation should establish an internal task force, with representatives from all the Directorates and the Office of Polar Programs, that would meet regularly to ensure that the new GIScience activity includes and benefits all relevant parts of the Foundation and their constituents.
4. The Foundation should appoint a multidisciplinary advisory panel of non-NSF personnel to assist in defining, implementing, and evaluating the effectiveness of this activity.

The University Consortium endorsed these recommendations for GIScience in June 1999.

Visions from 2010

Technological trends suggest that the world of the scientist will be very different a decade from now. Information technology, communications infrastructure, microelectronics, and related technologies could enable unprecedented opportunities for discovery, and new ways to do research. To make this more concrete, here are some visions of some aspects of the practice of geospatial[1] research in the year 2010.

- A geomorphologist doing fieldwork at a Long Term Ecological Research site in New Mexico slips on a headset as she leaves the site office. The headset combines glasses, earphones, and a tiny microphone, and weighs little more than a pair of sunglasses did in the 1990s. When she reaches her study area, she issues a simple voice command, and a red wire-frame display of the microtopography of the hill slope as it was surveyed by a graduate student who worked here in 1997 is superimposed on the landscape in front of her. Her **enhanced reality** system lets her see areas where there has been significant erosion over the last decade, since there, the older surface appears like a net stretched above the ground. After examining this simulated surface for a while, the researcher takes out a hand-held pointing device, and begins to point at the current surface in various places and click on them. As she works, a green mesh appears, connecting the points she has collected, and in places where it appears too far above or below the land surface, she collects additional points to make the digitized data fit the real micro-topography. Over the next several hours, she asks for a report on the total volume of material removed in one area since the 1997 study, and views a simulation of the runoff and erosion that might result from a 5 cm per hour rainstorm. As she works, her data appear simultaneously in the LTER data office and in the lab at the east-coast university where she is based, allowing her colleague to ask her for more surface height data in a nearby area. The next day, she wears a slightly heavier headset that incorporates a digital camera, so that an 8th grade science class in Oklahoma City can join her for a half hour to see how fieldwork happens, asking her questions in real time...
- A sociologist is studying crime in a city in the northeastern United States, trying to understand the pattern of assaults. Sitting in front of a multimedia system, he requests that all assaults in the past year be shown on a map of the city. While he is looking at the map, the system computes correlations with other available data, and notes several phenomena that have spatial associations with the crime data. One of these is an association between the pattern of assaults and the density of bars (drinking establishments); the researcher accepts this particular suggestion, and the system adds the bar locations to the map. Next, the researcher opens a modeling window and composes a rule: a "bar assault" is any assault within 100 meters of a bar, between the hours of 5 p.m. and 2 a.m. local time. He then asks for all bar assaults to be shown as yellow dots, and to display assaults that are not bar assaults in red. Next, he has the system show area lighting, traffic patterns, and police patrol patterns. The system automatically runs standard correlations and plots summary associations so that individual events can be examined. The variables with the highest correlations appear in a window, ordered from strongest to weakest correlation, and the system asks if he would like to see correlations between similar variables that have been published in similar studies of other U.S. cities. The system is providing this **spatially enabled scientist** with tools and methods to facilitate spatial thinking and inference, spatial analysis, and spatial statistics. The system automatically finds background data he requests, based on either coordinates or place names, checks that the data are compatible in terms of scale, accuracy, and map projection, and integrates data from different sources automatically, leaving the researcher to concentrate on thinking about the crime patterns themselves and their possible causes...
- Members of the general public, including school children, are obtaining detailed information about any place on Earth through an intuitive interface that looks like a large manipulable globe. They rotate the globe to put any region in the forefront, or simply speak to the system to ask it to show a particular place or region. As they zoom in, they see ever-increasing detail. The default view shows what the planet looks like at the current moment from the chosen perspective, but the user can ask for clouds to be removed, for the entire planet to be illuminated, or for thematic information such as political boundaries, population densities, endangered species, or land values to be shown. One person uses the system to travel back in time to look at agricultural patterns in southern Mexico in 1450. Another turns the time back half a billion years, and then watches continents form and move into their present positions. Yet another travels into a possible future world in a global warming scenario; to produce the images, the system invokes a Global Climate Model developed several years earlier in a research center that has been made available to the public through this **digital earth**. Although people without technical training easily use the digital earth, scientists and policy makers also use data from digital earth as input to their models...

These scenarios may seem like science fiction, but much of the technology to support them is already available in prototype form or is being developed: high-speed wireless information links, real-time multimedia satellite transmission, high-performance computing, global positioning systems (GPS) chips, content-based retrieval from digital libraries. The development and dissemination of such systems requires substantial advances in our knowledge of GIScience, associated knowledge of human-computer interaction, and models of environmental and social processes that shape our geographic world.

A Need for Research

Dramatic developments in communication, information and computational technologies alone promise to revolutionize our lives even further. Advances in these fields will change the way science is performed and expand its capabilities dramatically. They will influence the ways we teach and learn—perhaps even the way we think. Our scientific adventures are far from over.[2]

GIS and spatial analysis methods are powerful tools for the analysis and synthesis of geographically distributed phenomena, and form a critical component of the information infrastructure for science. Such systems are applicable to a wide variety of problems, including many areas of basic and applied research. GIScience is an inherently multidisciplinary field that underpins GIS.[3] The GIS software, data, and services industry is estimated at $4.2 billion in the United States alone, and appears to be growing at around 20 percent per year.[4] GIScience research, and research *using* GIS, have been funded by the National Science Foundation through a wide range of programs and other activities, including every Directorate to some degree. However, except for a special solicitation issued in 1987 to establish the National Center for Geographic Information Analysis, no program or special activity has focused explicitly and directly on GIScience and GIS.

In order to explore this situation, a workshop was held at the National Science Foundation on January 14-15, 1999.[5] The goals of the workshop were to explore the relationship of GIScience to existing programs and initiatives at NSF, and to examine the prospects for new initiatives or other activities in the area of GIScience and geospatial information. Twenty researchers from outside the Foundation, representing many of the disciplines and fields active in and dependent on GIScience, participated in the workshop, along with many members of the NSF staff. The participants are listed in the Appendix to this report.

In the remainder of this report, we first distinguish two distinct but deeply interconnected research areas: basic research in GIScience; and research using GIS. We present arguments regarding why research in both areas is critical to the advancement of our knowledge of geographic information. They should both receive special funding emphasis at NSF, and the funding should be awarded to catalyze multidisciplinary research that integrates two research domains where possible. After reviewing four major computing problems that have a role in GIScience research, we outline several trends and opportunities in science, technology, and policy that would make an immediate NSF response very timely. After providing a summary of the community that would be likely to respond to an NSF activity in GIScience and Geospatial Activities, we close with specific recommendations to the Foundation.

Research Using GIS

The early development of GIS was led by applications in land management and record keeping in government. GIS also have become powerful tools for researchers in the environmental and social sciences. GIS can support both exploratory and confirmatory analysis, provide tools for both inductive and deductive approaches, and support both scientific research and the implementation of public policy based on GIS models. However, GIS and geospatial technologies are not used in research as widely as they could be or should be. One major barrier is the lack of **interoperability** among GIS and geographic information technologies themselves, and between GIS and other information technology. Research communities often have their own software for pre-processing of sensor data or for analysis; however, due to the nature of commercial GIS, it may be difficult or impossible to integrate such software with components of commercial GIS, or to rewrite scientific models in the macro- or modeling languages of GIS. Problems arise due to inadequate documentation of data quality, and the propagation of error through GIS or other analysis. Differences due to scale and resolution also impede GIS adoption in some sciences. Second is a barrier related to **dimensionality and temporality** of geographic phenomena–current commercial GIS are essentially 2-dimensional and static. The scientific focus on processes and explanation of environmental phenomena may require three spatial dimensions, or time, or both, and this requires extensions to geographic representations available in GIS. Third is an **ease of use barrier**. Most GIS software today is not easy to use, but requires extensive training. Issues of human-computer interaction impede scientific adoption of GIS, especially in fields where computer literacy is not high. Across many scientific domains, researchers using geographic information struggle when they attempt to compare or integrate their data with data collected and processed by others. Important insights can be lost due to this impediment, which arises because of a lack of theory and methods to perform integration of geospatial information across different data models, scales, and phenomena. Identifying and tracking derived or processed information relative to primary information also is a critical issue.

There is wide variability in the levels of adoption of GIS, spatial analysis, and related tools and methods across the environmental and social sciences. Scientific advances often are driven by the availability of both analytical tools for analysis and data required by those tools, and some sciences are missing out on the insights that could be provided through spatially-explicit problem solving enabled by GIS. For example, several impediments to greater use of GIS by geologists have been identified, and are typical of many other fields as well:

- the lack of 3- and 4-D oriented spatial analysis tools; these include mathematical, cognitive, and statistical tools;
- the inability of generally available systems to accurately depict the natural variability of geologic features, or to represent associated uncertainties;
- the lack of access to subdiscipline-specific tools for exploring and modeling geologic systems– for example, many such tools have been developed for the oil industry but are too expensive for all but a few universities to obtain; and
- the lack of well done examples to help break the inertia of science. Most geoscientists know about GIS, but do not embrace it because they wonder if the investment in time, effort, and research dollars to deal with GIS will result in better science.

These or similar impediments likely are applicable in most of the environmental and social sciences. But if and when such impediments are overcome, GIS can have a significant role in accelerating diffusion of ideas across the disciplines. And since untrained viewers often can understand maps and other graphic displays, GIS can serve an important role in communicating science to the public.

Research in GIScience

GIScience is the basic research field that seeks to redefine geographic concepts and their use in the context of GIS. GIScience also examines the impacts of GIS on individuals and society, and the influences of society on GIS. GIScience re-examines some of the most fundamental themes in traditional spatially oriented fields such as geography, cartography, and geodesy, while incorporating more recent developments in cognitive and information science. It also overlaps with and draws from more specialized research fields such as computer science, statistics, mathematics, and psychology, and contributes to progress in those fields. It supports research in political science and anthropology, and draws on those fields in studies of geographic information and society.

GIS are similar to many statistical packages, in that they are commercial software systems widely used both within and outside the research community. However, there is an important difference between the two areas: statistics has a more universally agreed-upon foundation, whereas there is not yet an equivalent mature foundation for GIS software. GIScience seeks to provide the theoretical foundation for GIS, just as the discipline of statistics provides foundations for statistical software. Again as in the case of statistics, basic research in GIScience is a legitimate (though young) scholarly enterprise in its own right. But the positive effects of GIScience on the GIS software industry, and on basic and applied research using GIS, are inescapable. And GIS are used in some of our most pressing societal problems, such as crime, health, and disaster response.

Basic research in GIScience addresses complex problems that require multidisciplinary solutions. Fundamental problems in such a field are at risk of falling through the cracks between traditional disciplines, especially in the absence of targeted funding to support it. GIScience may begin with deep ontological questions regarding the nature of space and phenomena in space. Is the concept of space itself different among different fields of study? If there are differences, what are the common elements? Results from studies of spatial cognition and spatial language have rarely been used to build spatial query languages, and work in robotics on objects moving in space over time cannot easily be integrated with work on spatio-temporal databases for moving objects. Even methods of spatial analysis developed in geography and regional science are often difficult to integrate into a GIS framework.

The Need to Integrate Theoretical and Applied GIS Research

The workshop participants strongly endorsed an integrated approach to both kinds of GIS-related research. This research field is clearly an area in which applications motivate the science. Difficulties encountered in applying GIS to spatial problems and phenomena can expose interesting and significant problems requiring basic GIScience research for their solution. Likewise, awareness of theory can improve applications, putting them on a solid conceptual foundation.

Enabling GIS Use through GIScience

Integration, scale, process models, and usability are major research issues facing GIScience. These research issues apply to a wide range of domains where digital computers are employed, but many of the specific answers that GIS needs are unique to geographic information, and require GIScience research for their solution

Integration

Market forces that promote software integration and interoperability in business have not had as much effect on scientific software, which often has been developed with the narrow needs of a specific research community in mind. Existing tool systems do not always make it easy to respond to new technologies for data collection or processing, and the problem is complicated by uneven levels of technical abilities and training across the disciplines. GIS can serve as a frame for scientific data integration, but there are conceptual impediments to the integration of some scientific models with software. Data fusion is an integration problem, and conflation, the process of combining spatial data from different sources, is also critical. When geospatial data from different sources are combined, it is a challenge to preserve the semantics inherent in the component data sets, unless each was prepared strictly according to a common standard. Data quality for the results of data fusion or conflation may be difficult to characterize, especially with regard to positional accuracy.

Scale

Even without formal training in cartography, most people realize that the scale of a paper map influences the amount of detail that can be portrayed. But they may not realize how pervasive the influences of scale and resolution are on the analysis and other use of geospatial information in computers. Some of this is a legacy effect, since much geospatial information today was derived from maps. And for remotely sensed imagery, spatial resolution is a characteristic of the design of sensing instruments. Different measurement and positioning technologies will usually produce data with different positional accuracy, capable of resolving different levels of detail in geographic phenomena. A great deal of other geographic information is available not for points but for zones. For example, census data, a cornerstone of much social science research, are spatially aggregated in order to protect the confidentiality of individual records. The aggregation rules are based on a minimum population, and thus are larger in low-density areas and smaller where population density is high. The zones may also change from one census to the next. Simulations have shown that correlations between variables may vary considerably under different aggregation scenarios, calling into some question findings that are based only on analysis of data for the zones that happen to have been selected by the census bureau. Such scale or aggregation effects are not restricted to the social sciences but have been addressed in ecology as well. If basic GIScience can produce new methods of analysis that can minimize effects of scale and resolution of new and legacy geospatial data, this would have significant benefits for fields conducting research that uses geospatial information.

Process Models[6]

There is much knowledge embedded in the processes carried out to solve problems. Exploitation of geographical information not only requires having the right maps, but also requires knowing how to use them. The science of describing process knowledge is much less advanced than the science of describing data. For instance, even a simple task such as a search for the nearest restaurant cannot now be expressed effectively in any of the tools available on the Web. For spatial searches, these algorithms are closely linked to geographic representations, and there is a recognized interplay between process models and information representation that is poorly understood. Research, experiments, and development are required to make the wealth of the data that is becoming available fit the tools of the researchers and the public. Some of the key research topics here are spatial dynamic modeling, non-linear transformations, linkage and integration of process models with information systems, computability, and validation. The computability dimension may include heuristics to determine which solution method to use, based on the size and difficulty of the problem.

Usability

Usability often refers to issues of human-computer interaction (HCI), user interface design, and training. Indeed, these issues are of central importance, since if the user does not understand the system and its user interface, the system will at best be used inefficiently, and at worst will be used incorrectly and produce invalid results. At the workshop, though, participants put usability in a much broader context. Access is an important factor in the ability of a particular person to use GIS: access to data, access to processing power, access to technology, access to training—all of these influence system use. More broadly yet, are people aware that systems and data exist at all? If so, how can they find out what data are available, whether they are fit for use? Issues of how users communicate their needs to the system get us back into HCI. Typing and mouse clicks are not the only means of interaction, but the potential of other interaction methods such as sketching, touch screens, and voice have hardly been examined for the geospatial context. The usability issue should also examine more deeply the potential value of collaborative decision-making across distances for spatial decision support. Usability also has a societal context: a single system, based on the same data, should be able to adapt to serve the needs of different sub-populations with different backgrounds and needs.

Research Challenges

A different way to motivate basic research is through grand research challenges. The workshop program did not allow time for consensus building regarding such challenges, but in the opening session of the workshop, one of the participants presented four grand challenges for GIScience. Although they reflect the particular priorities and curiosities of one workshop participant, they are representative of the fundamental scientific questions that will drive GIScience in the next decade.

Challenge 1: Representation

The central idea here is the challenge of representing the infinite complexity of the real world within the digital computer. The real world is usually thought of as a spatio-temporal continuum, whereas the digital computer has finite capacity, and represents concepts and values in a discrete code. To meet this challenge, GIScience must examine the geographic concepts that are used by environmental and social scientists in their research, including the ontology of reality at geographic scales. GIScience research in this area will be conducted by experts in geographic theory and geographic representations, by domain scientists who study geographically distributed environmental and social phenomena, by knowledge engineers and information scientists, and by philosophers.

The challenge: To find ways to express the infinite complexity of the geographical world in the binary alphabet and limited capacity of a digital computer.

Challenge 2: Uncertainty

If the representational challenge cannot fully be met, we must accept that geospatial data include uncertainty. This uncertainty can include measurement error, error due to imperfect interpolation between measurements, gaps (incomplete data), artifacts of graphic or digital processing, and occasional blunders. Or it may be due to the nature of the phenomena themselves, such as the extents of objects with indistinct or graded boundaries. The scientific measurement model is available for some aspects of uncertainty, but strong spatial dependencies complicate the situation considerably. And some spatial processes are essentially stochastic, and thus have an inherent uncertainty component.

The challenge: To find ways of summarizing, modeling, and visualizing the differences between a digital representation and real phenomena.

Challenge 3: Cognition

Although some information comes directly from sensor into spatial databases, human operators who use human judgment in their work have developed much geospatial information. Data from maps have been through processes of symbolization, abstraction, and generalization. Thus inclusion of map-based information in GIS means that cognitive concepts are already incorporated into spatial databases. Many spatial or geographic abilities are part of common knowledge or common sense and are characteristics of most people by the time they reach the age of 12. Use of GIS and spatial analysis tools may depend on these abilities, but also on other concepts not learned until graduate school. In some ways, this is similar to the challenge of representation, except here it is the correspondence between binary representations, computational methods, and cognitive concepts that is the focus.

The challenge: To achieve better transitions between cognitive and computational representations and manipulations of geographic information.

Challenge 4: Simulation

It could be argued that one cannot claim to have understood a process if one cannot build a computer simulation of that process whose output cannot be distinguished from data about real-world instances of the process. Part of the popularity and impact of fractal mathematics has been the degree to which graphic renderings of fractal functions simulate, to some degree, landscapes or other natural phenomena. In detail, however, fractal mathematics has little in common with geomorphic processes, and an expert could quickly distinguish fractal terrains from real ones. Successful simulation of geographic phenomena would not only provide a way to confirm process geographic processes, but it also can provide generic data for testing algorithm performance, graphical procedures, and other GIS methods.

The challenge: To create simulations of geographic phenomena in a digital computer that are indistinguishable from their real counterparts.

The Data Challenge

One additional technological trend that requires a response is the increasing quantity of data being collected and archived. The fact that very large volumes of scientific data were becoming available was already evident in the late 1980s, but a dozen years later, data volumes are drastically higher again. Commercial remotely sensed data will soon be available at 1-meter resolution. Locally-produced data is being registered on the Internet in the clearinghouses of the National Spatial Data Infrastructure, and with GPS and wireless technologies making even more data available, the flood of geospatial data will be spectacular. However, the existence of unimaginable quantities of data does not guarantee that researchers will find needed data more quickly and easily. Just as Coleridge's ancient mariner was thirsty when becalmed in a vast ocean, the current scientists cry could be "Data, data everywhere, but not the information I need." This will be a problem for all kinds of data of interest to scientists, but solutions for geographic information will need focused research efforts. Even if the right data can be found, complex problems need sophisticated tools that may fail to be useful or usable, for reasons noted above.

The visions for 2010 presented in the first part of this report will be difficult to realize if the major research issues and grand research challenges presented in this section are not met head on by a concerted, coordinated program of multidisciplinary research. Such a research program will required the participation of national funding agencies.

Trends and Opportunities

Why now?

Research using GIS has been happening for decades, as has research into basic theories and concepts of computing about geographic space. But, as noted above, current technologies and societal trends are producing great increases in availability of and demand for GIS and services by all sectors of society. The technology and systems will continue to be pushed by military, commercial, and administrative applications, and the research sector is small by comparison. Without investment on behalf of the research community, the full potential of these systems and technologies for scientific use is unlikely to be realized. Funding from the margins of other disciplines and programs is unlikely to provide the kind of base funding that this emerging multidisciplinary field of study requires.

The President's Information Technology Advisory Committee[7] was established to provide the government with guidance and advice on all areas of high performance computing, communications, and information technologies. The Interim PITAC Report submitted in August 1998 noted that under funding of research related to information technologies is a threat to "U.S. leadership in the emerging 21st-century information-based economy." The worldwide market for GIS software and services has been projected to approach $4 billion in 1999, and U.S. companies appear to have more than half of the world market for GIS software. Including services as well as software and data, 1998 market in the U.S. alone is estimated at $4.2 billion.[8] The U.S. GIS industry is very healthy at present, but could stall out in the future without sufficient government support of basic research into the theoretical foundations of GIScience. Many aspects of current commercial systems are based in innovations developed in the public or academic sectors in the 1960s and 1970s. The PITAC report specifically mentions GIS in a section on socio-economic impacts of an investment in information technology research.

If the PITAC report leads to increased funding for basic research in information science and technology, a non-trivial proportion of those funds should be specifically directed toward GIScience research. The general public easily understands many aspects of GIS and related technologies, and an investment in this area is likely to produce tangible benefits obvious to many sectors of society. Such investment could also help assure that U.S. industry will continue to lead in this area. GIS software also serves other industries, and is used in data management by all levels of government. The Next Generation Internet (NGI) and the development of a Global Disaster Information Network (GDIN) are other trends that are consistent with the need for further advances in GIScience and related technologies. Mobile information systems with positioning systems will provide new opportunities and challenges for the telecommunications industry, and have positive implications for the broader field of information technology.

Why NSF?

GIScience needs a broad, cross-disciplinary coverage and active involvement of researchers in order to make necessary advances. GIScience needs research in theoretical geography, mathematics, cognitive science, and basic computer and information science, as well as in areas of science and engineering where GIS is applied to scientific problems, such as ecology, earth science, social sciences, and other areas. Clearly, GIS and GIScience research should be supported by many federal agencies. However, the National Science Foundation is the only agency in the United States that supports all aspects of the GIScience and GIS, from theoretical topics to scientific applications. The National Science Foundation is well placed to make a difference to scientific and technical progress in GIScience.

There are parallel initiatives already being planned within the Foundation as well. NSF's Directorate for Geosciences (GEO) is undertaking a major long-range planning effort to develop a vision of the cutting-edge issues for the geosciences during the first decade of the 21st century.[9] One of the driving forces behind this effort, code-named "GEO Beyond 2000," is improved scientific models, and the other is technology.

The second development is the revolutionary increase in the capability of computer information, and sensor technologies. Our current ability to monitor and observe the Earth system on all spatial and temporal scales is unprecedented, and, when coupled with our ever-increasing ability to store and retrieve vast quantities of archived information for detailed examination, provides for much more rapid knowledge generation and dissemination. These rapidly improving technologies will advance the scientific research to provide the sophisticated tools and monitoring systems that policy makers will need to make informed decisions.

If GEO Beyond 2000 goes forward, it could contribute significantly to needs for 'Research using GIS' in the geosciences. However, it is unlikely that it would provide the broad multidisciplinary support for basic GIScience and for research using GIS in the biological and social sciences.

"This Just In..."

In the months following the workshop, potential support for computer and information science and technology continued to improve. The U.S. Administration's FY 2000 budget includes $366 million of new money for computing and communications technology, to be implemented through several Federal agencies, of which NSF's $146 million is the largest component.[10] NSF's FY 2000 budget[11] states:

> NSF has been asked to serve as lead agency for the Administration's FY 2000 Information Technology for the Twenty-First Century (IT^2) initiative. IT^2 grew from the efforts of several agencies and responds to recommendations made by the President's Information Technology Advisory Committee (PITAC), which termed federal support for information technology "dangerously inadequate". Partner agencies include the Departments of Defense and Energy, the National Aeronautics and Space Administration, the National Institutes of Health, and the National Oceanic and Atmospheric Administration. IT^2 involves a total federal investment of approximately $366 million in FY 2000. NSF's FY 2000 investment in IT^2 totals $146 million. This includes $110 million funded through NSF's Computer and Information Science and Engineering Activity for research in software systems, scaleable information infrastructure, and high-end computing.

The participants in the present GIScience workshop felt that specific GIScience research is needed to solve geospatial dimensions of information technology, we recommend that a portion of any increased research money for information technology be directed specifically toward GIScience.

A Research Community Ready to Respond

Funding initiatives such as the one we are recommending are unlikely to be effective in the absence of a community of scholars that provides both potential applicants as well as norms against which proposals would be evaluated. GIScience in the United States has such a community. Although the term Geographic Information Science was coined only in the early 1990s, it labeled a science and engineering field that had been emerging during the previous two decades as a consequence of technological transitions in the mapping sciences, convergence of spatial analysis methods, and the development of new technologies for collection and processing of geospatial data. In 1994, representatives of 34 U.S. universities and other research organizations met and decided to establish an organization "dedicated to the development and use of theories, methods, technology, and data for understanding geographic processes, relationships, and pattern." Named the University Consortium for Geographic Information Science (UCGIS), the organization has grown to include 50 universities and four other organizations as full members, and some of the leading U.S. IT and GIS firms as affiliate members.[12] The University members are estimated to have more than a thousand individual GIS-related researchers and educators, and these are only part of the U.S. academic research community. In 1996, the UCGIS established 10 "National Research Priorities" that have been used to promote research in the field,[13] and in 1997, they determined eight "National Education Priorities".[14] Taken together, the UCGIS research priorities cover a rather broad range of specific research problems in GIScience, and thus these priorities have a different granularity from the research areas discussed in this report. Other resources for the field include the National Center for Geographic Information and Analysis and its current Project Varenius ("Advancing Geographic Information Science"), the Open GIS Consortium, the Federal Geographic Data Committee, and a good number of refereed journals[15] and scholarly conferences. The OpenGIS Consortium[16], established in 1994 to provide a formal structure and process for developing a specification for interoperable geoprocessing, is another indication of a research and development community. Primarily composed of private sector organizations, OpenGIS also includes government and academic participants. Thirdly, in the public sector, the Federal Geographic Data Committee (FGDC)[17] was established by a Presidential Order, also in 1994, to support public and private sector applications of geospatial data in such areas as transportation, community development, agriculture, emergency response, environmental management, and information technology; state and local governments are involved through the National States Geographic Information Council (NSGIC) and the National Association of Counties (NACo).

Methods and Levels of Funding

In a climate where research funding is widely acknowledged to be tight, it is difficult to know what level should be devoted to new activities in GIScience. There are, however, several recent or future tendencies that may provide some basis for such decisions. For example, recently, NSF devoted $50 million per year to the Knowledge and Distributed Intelligence (KDI) initiative. For the future, the PITAC report recommended a diverse portfolio of funding for information technology, including single-investigator efforts, multi-investigator projects, and centers. One of the more novel ideas presented in the PITAC report is "Expeditions into the 21st Century," described as follows:

> "Expeditions into the 21st Century" will be virtual centers that bring together scientists, engineers, and computer scientists from academia, government, and industry to "live in the technological future." The mission of these expeditions will be to report back to the Nation what could be accomplished by using technologies that are quantitatively and qualitatively more powerful than those available today.

They recommend that such Expeditions be very well funded:

> The full term of an Expedition would be ten years. To encourage truly aggressive efforts, very high annual funding levels should be possible, say up to $40 million per center.

PITAC also recommended "Enabling Technology Centers" at up to $10 million per year.

The workshop participants believe that investment on that order of magnitude is needed to have a real influence on amount of basic GIScience research conducted and the number of disciplines now using GIS and geospatial methods in their research. Considering the size of the U.S. GIS industry and of government annual expenditures on GIS, GIScience research funding on the order of $40 million per year is readily justified. NSF has available many models for administering and funding research, ranging from individual proposals and programs to cross-Directorate initiatives and Centers. Educational initiatives should not be ignored, nor should physical infrastructure such as computing hardware or buildings to house GIScience research activities. Geographic information pervades, or should pervade, all computing about the environment and society, for administration, management, planning, disaster response, and business as well as applied research. GIScience provides the basic intellectual underpinnings for geographic information technologies, and GIScience research should be supported at levels appropriate to the importance of these technologies and their application.

Recommendations

The workshop participants make the following recommendations to the National Science Foundation:

1. The National Science Foundation should recognize the importance of GIScience as a coherent research field, and should establish a funding activity in this area as soon as possible.

2. Both basic GIScience, and research using GIS, should be supported from the new activity, to promote the integration of these research areas.

3. The Foundation should establish an internal task force, with representatives from all the Directorates and the Office of Polar Programs that would meet regularly to ensure that the new GIScience activity includes and benefits all relevant parts of the Foundation and their constituents.

4. The Foundation should appoint a multidisciplinary advisory panel of non-NSF personnel to assist in defining, implementing, and evaluating the effectiveness of this activity.

At its Council meeting on June 26 1999, the University Consortium for Geographic Information Science passed a resolution that "UCGIS strongly supports the recommendations to NSF set forth in the NSF-funded workshop report titled 'Geographic Information Science: Critical Issues in an Emerging Cross-Disciplinary Research Domain'."[18]

Appendix A: Workshop Participants

Workshop Co-Chairs:

David M. Mark, Geography, State University of New York at Buffalo
Leal A. K. Mertes[19], Geography, UC Santa Barbara
Richard R. Muntz, Computer Science, UCLA

Steering Committee:

Max J. Egenhofer, Spatial Information Science and Engineering, University of Maine
Michael F. Goodchild, Department of Geography, University of California-Santa Barbara
Charles M. (Chuck) Meertens[20], UNAVCO
Barbara Tversky, Psychology, Stanford University

Other Workshop Participants:

Lawrence E. Band, Geography, University of North Carolina
Roy K. Dokka, Geology and Geophysics, Louisiana State University
Susan L. Epstein, Computer Science, Hunter College, City University of New York
Stephen C. Hirtle, Information Sciences, University of Pittsburgh
David R. Janecky, Geochemistry, Los Alamos National Laboratory
Carol A. Johnston, Natural Resources Research Institute, University of Minnesota, Duluth
Stephanie King, John A. Blume Earthquake Engineering Center, Stanford University
Werner Kuhn, Geoinformation, University of Muenster, Germany
Harvey J. Miller, Geography, University of Utah
Donna J. Peuquet, Geography, Pennsylvania State University
Hanan Samet, Computer Science, University of Maryland
Eric S, Sheppard, Geography, University of Minnesota
Michael Stein, Statistics, University of Chicago
Thomas M. Usselman, Earth Sciences, National Academy of Science
Gio Wiederhold, Computer Science, Stanford University

NSF Observers:

Frank D. Anger, Computer-Communications Research, CISE
Thomas J. Baerwald, Deputy Assistant Director, GEO
Bernard O. Bauer, Geography and Regional Science, SBE
Bennett I. Bertenthal, Assistant Director for SBE
Scott G. Borg, Office of Polar Programs
Lawrence E. Brandt, Experimental and Integrative Activities, CISE
John M. Briggs, Ecology, BIO
John C. Cherniavsky, Senior Advisor for Research, EHR
Alan M. Gaines, Senior Science Associate for Spatial Data and Information, GEO
Julie Palais, Office of Polar Programs
Rita V. Rodrigues, Experimental and Integrative Activities, CISE
James L. Rosenberger, Statistics and Probability, MPS
Michael H. Steuerwalt, Applied Mathematics, MPS
Maria Zemankova, Information and Data Management, CISE

Notes

1. The term *geospatial* is used in this report to refer to spatial information (positions, sizes, shapes, orientations, relations) for phenomena at geographic scales. In contrast, spatial information could refer to the same characteristics at any scale, from sub-molecular to intergalactic. Geographic information is used to refer to both geospatial and non-spatial attributes of geographic phenomena.

2. House Committee on Science, 1998. Unlocking Our Future: Toward a New National Science Policy: A Report to Congress. http://www.house.gov/science/science_policy_report.htm

3. In this report, we take a broad view of GIS as any software for handling geographic information, and do not limit the term to current commercial off-the-shelf software.

4. National Academy of Public Administration, 1998. Geographic Information for the 21st Century: Building a Strategy for the Nation. Washington, DC: National Academy of Public Administration, Report 98-01, p. 298.

5. Funding for this workshop was provided by the National Science Foundation, through a supplement to award SBE-9600465. Support from the Foundation is gratefully acknowledged. In addition to the members of the Steering Committee, Bernard Bauer, Alan Gaines, and Maria Zemankova (all of NSF) and Patricia Shyhalla (University at Buffalo) were especially helpful in the planning of the workshop.

6. The term *process model* is used here to refer to computational processes, and not to models of physical or social processes.

7. http://www.ccic.gov/ac/

8. NAPA report, 1998, op cit., p. 298.

9. http://www.geo.nsf.gov/adgeo/geo2000/

10. http://www.access.gpo.gov/usbudget/fy2000/pdf/budget.pdf, page 107.

11. National Science Foundation, Fiscal Year 2000 Budget Request, Overview. http://www.nsf.gov/bfa/bud/fy2000/overview.htm.

12. http://www.ucgis.org/

13. UCGIS, 1996. Research Priorities for Geographic Information Science. *Cartography and Geographic Information Systems* 23(3). http://www.ncgia.ucsb.edu/other/ucgis/CAGIS.html

14. http://www.ncgia.ucsb.edu/other/ucgis/ed_priorities/contents.html

15. *International Journal of Geographical Information Science, Cartography and Geographic Information Systems, Geoinformatica, Transactions in GIS, Geographical Systems*, *Spatial Cognition and Computation*, and others.

16. http://www.opengis.org/

17. http://www.fgdc.gov/

18. http://www.ucgis.org/CM-MN.html

19. Leal Mertes and Chuck Meertens are members of the workshop Steering Committee but were unable to attend the workshop.

20. See previous note.