Research challenges in geovisualization. Cartography Geograph.

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Research Challenges in Geovisualization

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This special issue of *Cartography and Geographic Information Science* presents the results of an international collaboration to delineate a four-part research agenda for geovisualization. Geovisualization integrates approaches from visualization in scientific computing (ViSC), cartography, image analysis, information visualization, exploratory data analysis (EDA), and geographic information systems (GISystems) to provide theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data (any data having geospatial referencing). Primary themes addressed here are *representation* of geospatial information, *integration* of visual with computational methods of knowledge construction, *interface design* for geovisualization environments, and *cognitive/usability* aspects of geovisualization.

The International Cartographic Association (ICA) Commission on Visualization and Virtual Environments took the lead in developing this comprehensive research agenda by organizing an international team to address each theme. The teams included both Commission members and others active in geovisualization and related areas. Participants represent a range of disciplines and include representatives from government and the private sector as well as academic researchers. Each team was assisted by an expert from outside geographic information science who provided critical review of white papers prior to completion of final manuscripts. The full set of manuscripts was then submitted to formal peer review. The research agenda development process is detailed on the commission web site at: www.geovista.psu.edu/icavis.

In this essay, we provide an overview of the organizational, technological, and scientific context for this research agenda setting effort, emphasizing changes in each that prompted the project at this time. Next, we outline the core issues identified within each of agenda theme and summarize challenges identified. Then, four cross cutting challenges are delineated. We conclude with recommendations for action.

Overview

Human vision and domain expertise are powerful tools that (together with computational tools) make it possible to turn large heterogeneous data volumes into information (interpreted data) and, subsequently, into knowledge (understanding derived from integrating information). Visualizing the world (through geospatial data) has been a cartographic concern for centuries. Still, the ICA recognized a need, in 1993, for a special effort to link cartographic research activities in visualization with those in other information science disciplines, particularly those prompted by the U.S. National Science Foundation sponsored ViSC report (McCormick et al., 1987). An initial ICA working group extended in 1995 to become the Commission on Visualization, then in 1999 reauthorized as the current Commission on Visualization and Virtual Environments. Through each stage, the group has emphasized research to enable science and society to cope with a rapidly increasing volume of geospatial data. Specifically, the goals have been to develop both theory and practice that facilitates knowledge construction through visual exploration and analysis of geospatial data, along with the visual tools needed to support subsequent knowledge retrieval, synthesis, and use.

Why focus on "geo" visualization?

Estimates suggest that 80% of all digital data generated today include geospatial referencing (e.g., geographic coordinates, addresses, postal codes, etc.). This referencing enables integration of vast stores of diverse information. At the same

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time, the magnitude and complexity of data sets brought together through their common geospatial links poses an extraordinary challenge for information science – *how do we transform these data into information, and subsequently into knowledge*.

Methods and tools for visualization in support of science have advanced rapidly with demonstrated successes in areas such as medical imaging, process model visualization, and molecular chemistry. In addition, a new discipline of Information Visualization has begun to emerge, with a focus on visualization of non-numerical information (Card et al., 1999). Still, *visualization is not being taken advantage of to exploit the full potential of geospatial data*.

Many core challenges being faced in the natural and social sciences have an inherent complexity and inter-disciplinary nature. Examples include: how to assess the vulnerability of regions and their human populations to global environmental change, how to measure and sustain biodiversity, how to predict and cope with changing disease incidence patterns, and how to manage the increasing traffic flows of cities more effectively. Geospatial referencing provides a fundamental mechanism for linking the diverse forms of data needed to attack these problems. We do not have fully-developed, integrated models of complex human and environmental systems, thus integrating data is not enough. Geovisualization has the potential to provide 'windows' into the complexity of phenomena and processes involved, through innovative scene construction, virtual environments (VEs), and collaboration, thus prompting insight into the structures and relationships contained within these complex, linked datasets.

Current visualization methods and tools have not been designed to deal with the unique geospatial characteristics of data critical to these problems nor to take full advantage of georeferencing as a mechanism for fusing data from diverse sources. Geospatial data (and the geospatial information derived from them) are fundamentally different from other kinds of data (and information) in at least three ways.

First, geospatial data are inherently structured in two (latitude and longitude), three (position above or below the Earth's surface), or four (time) dimensions, while often unstructured in others. Thus, distances and directions among entities and locations have real meaning in geographic space. The inherent structure can be exploited to enable efficient data access with very large databases. That same spatial structure poses problems for traditional statistically based methods of analysis (used either alone or in conjunction with visualization, i.e., problems of spatial autocorrelation). Thus, different approaches must be developed for integrated visual-computational analysis of these data.

Second, many objects in geospatial databases have meaningful and useful names that can be taken advantage of in both database access and analysis. As with inherent structure of geospatial data, however, the match between geographic names and objects is complex and varies in explicitness. Geographic names for human constructed objects (e.g., county, road) have precise matches with location in the world while those for natural objects (e.g., mountain, flood plain) often do not.

Third, geographic scale is a critical but complex issue, with different geospatial datasets often containing emergent behavior at different scales. To capture scale-dependent phenomena and processes, geospatial data are typically collected at multiple scales, with fundamental differences in entities and their semantic structure across scales. For example, things defined as objects at one scale (e.g., residential buildings or a thunderstorm event) may be conceptualized as fields at another (e.g., a land use zone or an average precipitation surface), or not represented at all. While multi-scale data integration and analysis is a common problem in science, the diversity in kinds of phenomena brought together in geospatial analysis (for example, modeled climate data, aggregate demographic statistics, highway and river networks, soil classifications, quantitative and qualitative survey results, satellite remote sensing) makes geospatial scale issues particularly challenging.

Geovisualization and cartography

Cartography provides a rich history of both practice and science relevant to current geospatial visualization challenges (and to ViSC challenges more broadly, (Collins, 1993)). The technological, scientific, and social environment in which cartography operates, and in which maps are produced and used, has changed dramatically over the past two decades. Fundamental changes have occurred in acquisition, management, analysis, and cartographic representation of geospatial data, and map products can be produced much faster and less expensively than in the past. The World Wide Web has become the prominent medium through which to disseminate geospatial data and maps. The maps produced and disseminated are no longer limited to static form or 2D format, but can take advantage of immersive and highly interactive virtual environments to explore and present dynamic geospatial data. As a result of these changes, maps provide a more valuable window on the world than ever before.

In the past, paper maps were designed to be both database and presentation media. The advent of digital cartography and GIS, in the 1960s, split these tasks. Recent developments are making it possible to rejoin data storage with display, in ways never before possible. The map is now an interface that (if well designed) can support productive information access and knowledge construction activities (while it retains its traditional role as a presentation device). In modern map-based environments, the map can literally use the World Wide Web as its "database."

Modern cartography, thus, deals with a complex process of geospatial information organization, access, display, and use – with "maps" no longer conceived of as simply graphic representations of geographic space, but as dynamic portals to interconnected, distributed, geospatial data resources. Today's cartographic environments are characterized by two keywords: interaction and dynamics. While visual representation remains a fundamental issue, the focus of both cartographic design and cartographic research now extends to problems in human-computer interaction and in enabling dynamic map and map object behaviors.

This cartographic attention to interaction and dynamics is consistent with the focus initially proposed for "cartographic" visualization – on personalized, highly interactive tools that facilitate a search for unknowns (see MacEachren, 1994). From this perspective, maps designed to support visualization go well beyond information presentation to support information exploration and knowledge construction. With exploration, an *abductive* process is followed, one in which display use starts without hypotheses about the data, and visualization tools assist in an interactive, unencumbered search for structures and trends, with one goal being to prompt hypotheses. Maps and graphics in this context do more than "make data visible," they are active instruments in the users' thinking process. As illustrated in the "map use cube" (figure 1), between the extremes of traditional map presentation and visual data exploration, map-based visualization also supports goal-driven analysis and information synthesis.

Themes and Issues

As noted above, our research agenda focuses on four primary themes: representation, integration with knowledge construction and geocomputation, interface design, and cognition-usability. Each team was free to interpret their charge as they identified core challenges for the field. Not surprisingly, some issues were identified as important research challenges by multiple teams. This overlap provides an opportunity to take different perspectives on key problems and signals some of the crosscutting geovisualization issues that are most critical to address. In this section, we highlight core issues identified within each theme and summarize the research challenges delineated.

Representation

Representation is, itself, a crosscutting theme. Dramatic changes in visual representation possibilities and data to be represented, coupled with the fundamental questions that arise as we try to take advantage of them, provide the driving force behind this research agenda effort.

With data, challenges for traditional representation methods are posed by very large, multivariate geospatial data sets that include both the third spatial dimension (e.g, volumetric atmospheric data) and time. New representational tools that help respond to these challenges include interactivity, animation, hyperlinking, immersive environments, and dynamic object behaviors.

Maps have represented the world successfully for centuries by making the world understandable through systematic abstraction that retains the iconicity of space depicting space. Advances in methods and technologies are blurring the lines among maps and other forms of visual representation and pushing the bounds of "map" as a concept toward both more realistic and more abstract depiction. As a result, there are a variety of unanswered questions about the attributes and implications of "maps."

The representation agenda team (led by David Fairbairn) focused on visual representation as it relates to five issues: semiotics and meaning (how visual depiction relates to underlying meaning), data (how visual depiction relates to interpretations and structures imposed on data), map use (how visual depiction relates to desired uses), map users (how visual depiction relates to human-computer interaction), and technology (how visual depiction can/should take advantage of technological advances). While the focus is on visual representation, underlying data representation issues as well as non-visual perceptible representation methods (using sound, haptics, etc.) are also addressed. Five challenge categories are delineated by this team (with four to eight specific challenges detailed in each). The categories are summarized here as follows:

1. *To develop a theory for georepresentation and formalizing representation methods*. Existing cartographic-geovisualization theory does an inadequate job of dealing with representations that support highly realistic (and immersive) display, multimodal signification, and flexible direct interaction with objects in the representation (that may exhibit their own behaviors).

2. *To develop new forms of representation that support the understanding of geospatial phenomena and space-time processes*. There is a need to take full advantage of technological advances that make it possible to personalize representation, generate complex multidimensional and dynamically linked views, merge representation with reality, and utilize non-visual perceptual channels. Similarly, there is a need to develop methods that help users navigate within complex representations and for imbuing representational objects with adaptive behaviors (e.g., building "smart" display objects that react to user behavior and problem context).

3. *To adapt representation methods to meet the changing nature of data to be represented*. A primary focus here is to develop representation methods that can cope with very large data sets (terabyte and larger), of high dimensionality, containing complex semantic relationships, that vary in certainty, and that depict processes over time.

4. *Adapting representation methods to the increasing range in kinds of task that visual geospatial representations must support*. A key challenge identified here is to develop a typology of geovisualization tasks, with knowledge discovery and decision making highlighted as tasks for which particular research attention is required.

5. *To take advantage of recent (and anticipated) technological advances in both hardware and data formats*. With hardware, the core issues involve adapting geovisualization to, and extending it through, wearable computers, mobile communications, immersive environments, and multi-user applications. With data, more attention must be directed to the multiple international developments in open standards for encoding both data and graphics.

Visualization-computation integration

While continued advance in geovisualization methods and tools is important, geospatial data volumes are so large and the interactions among variables so complex that human vision cannot be successful in isolation. Fundamental advances in our approach to (and success at) knowledge construction from geospatial data are most likely if we can integrate the advantages of computational and visual approaches. The goal of this integration is visually enabled knowledge construction tools that facilitate both the process of uncovering patterns and relationships in complex data and subsequent explanation of those patterns and relationships.

A focus here is on tools that can function in the absence of pre-determined hypotheses. Recent developments in three domains are relevant. First, is exploratory visual analysis, a multidisciplinary effort (that includes geovisualization) to develop visual approaches to data analysis. Second, knowledge discovery in databases (KDD) focuses on developing methods that find useful and valid structure in large volumes of data and providing some means of explaining it. Third, geocomputation directs attention to developing methods to model and analyze a range of highly complex, often non-deterministic problems related to geospatial data.

Specific issues addressed by the integration agenda team (led by Mark Gahegan) include: visual approaches to data mining, visual support for computational knowledge construction methods, and databases and data models necessary to make visually-led geospatial knowledge construction a reality. Challenges identified are grouped into three categories, summarized as follows:

1.*To develop visual approaches to geospatial data mining, thus to using visual methods for uncovering unknown patterns and relationships in large geospatial data sets*. Important issues are: what information is represented (explicit incorporation of spatial and temporal aspects of data in the process); how information is represented (what impact does representational choice have on human inference processes and what representation methods allow users to understand hypotheses used by computational methods); and the mechanisms provided for interaction with the information (particularly the potential of natural, multi-modal methods).

2. *To integrate visual and computational tools that enable human and machine to collaborate in the process of knowledge construction*. An overarching issue here is to develop a taxonomy of knowledge construction tasks or operations that, together, enable user expertise within a knowledge construction process. Other specific challenges are: to understand the process of visually facilitated knowledge construction (and the impact of visual and other characteristics of the analysis environment on that process); and to develop mechanisms that facilitate productive collaboration in knowledge construction among human experts and between human users and computational agents.

3. *To address the engineering problems of bringing together disparate technologies, each with established tools, systems, data structures and interfaces*. Four specific problems identified are: to develop computational architectures that support integrating databases with visualization, identify the database functions needed to support the real-time interaction demanded by visually-facilitated knowledge construction, determine the impact that underlying data structures have on the knowledge construction process, and develop mechanisms for working discovered objects back into a consistent data model.

In their summary of geovisualization-KDD integration challenges, the agenda team identifies **three crosscutting, priority issues** that must be addressed if the challenges are to be met. The **first** involves how to explicitly incorporate the location and time components of multivariate data within visual and analytical methods. The **second** involves how to represent geographic knowledge; specifically how to include the rich conceptual structures of this knowledge in computationally based models. The **third** involves the complementary process of incorporating geographic meaning within visualization environments. All three of these issues are hard problems that can be considered challenges in their own right.

Interfaces

For advances in visual representation and visually enabled knowledge construction to have the greatest impact, and to extend these methods beyond use by individual experts, complementary advances are required in geovisualization interface design. New interface paradigms are needed that support interaction with advanced forms of representation and analysis, that take advantage of multimodal methods for access to and interaction with information, that work on small mobile displays, that support group work, and that can be adapted to support individual differences.

This research agenda team (led by William Cartwright) identifies four central interface themes within which challenges exist. These are: interfaces and representation of geography, interaction (particularly navigation and manipulation), universal access, and practical implementation of interfaces using new technologies. Challenges related to these themes are grouped into six categories, summarized as follows.

1. *To develop the understanding and mechanisms for capitalizing on the potential of geovisualization to prompt creative thinking.* A fundamental question here is whether access to computers generally and many mediums of display specifically allow people to think differently. Related to this are questions about how to determine an answer, how to apply knowledge derived to interface design and geovisualization, how to identify creative thinking, and what theoretical perspectives are appropriate to addressing the question.

2. *To extend our understanding of metaphor for geovisualization and develop principles for selection of appropriate metaphors.* Components of this challenge include the ways in which geographic metaphors differ from non-geographic, the need to develop a more complete understanding of the cognitive and usability aspects of meta-

phor use and how these aspects might change in multi-sensory or collaborative environments, and the potential and implications of integrating multiple metaphors in environments for complex geospatial analysis.

3. *To investigate both interfaces to support the concept of a Digital Earth and the concept of Digital Earth as an interface*. The vision for a Digital Earth is to provide comprehensive multivariate, multiscale information about all geographic-scale aspects of the earth, its environment, and its inhabitants. Building an interface that supports access to and use of the massive distributed database requiredto support Digital Earth is a substantial challenge. A related challenge is to exploit the potential of landscape/globe metaphors for providing this interface.

4. *To extend our understanding of interface design to take advantage of the potential of virtual environments.* Although virtual environments are expected to facilitate understanding of complex geospatial information, most VEs are hard to use because there is a mismatch between the visually realistic 3D character of the environment and the tools currently provided for navigating through that environment or changing its parameters. Specific problems of importance here include developing controls and metaphors appropriate to interaction with different kinds of geospatial information representations and understanding the cognitive and usability issues involved in their use.

5. *To develop and assess formalizations for specifying interface operations appropriate to geovisualization environments*. The problem here is that standard graphical user interfaces do not support complex queries of databases linked to the visual display, nor do they enable flexible manipulation of display parameters. Alternatives that should be investigated include extension of visual programming concepts to and development of formal languages for geovisualization.

6. *To develop a comprehensive user-centered design approach to geovisualization usability.* Several specific objectives are identified here. Among them, there is a need to develop a better understanding of how ordinary users interact with geospatial displays. There is also a need (echoed by Slocum and colleagues in this issue) to develop formal methods for usability assessment applicable to geovisualization use. Finally, a typology of geospatial interface tasks is needed to structure both design of tools and formal testing.

Cognitive/usability Issues

The approaches taken to the three themes outlined above each raise issues concerning use and users of geovisualization environments. Whether our focus is on representation, knowledge construction, or interfaces, two common questions can be posed: does the tool work? and how? These questions, of course, have many dimensions. How will people react to fully immersive environments, can they deal with the information density offered, are the navigation tools provided effective, and what factors determine success or failure of geovisualization? Our current understanding is particularly limited in relation to individual and group differences related to experience, sex, age, culture, and sensory disabilities and to the use of visualization collaboratively. Answering these questions becomes more urgent since the "map" is being used increasingly as a metaphor in design of non-geospatial visualization tools.

The fourth research agenda team (led by Terry Slocum) addresses these issues directly, with a dual focus on cognition and usability. A fundamental problem for geovisualization is to understand (and take advantage of) the mechanism by which the dynamic, external visual representations offered by geovisualization serve as prompts for creation and use of mental representations. With usability, emphasis is on delineating the advantages and disadvantages of the increasing array of geovisualization methods and technologies, in a wide range of contexts for a wide range of users. A related issue is the current lack of established paradigms for conducting cognitive or usability with highly interactive visual environments, particularly when those environments are designed for application to ill-structured problems (e.g., knowledge construction or decision support). Challenges identified are grouped into seven categories.

1. *To develop cognitive theory to support, and assess usability of, methods for geovisualization used within virtual environments*. One issue here is to understand the implications of the natural forms of representation and interaction that VE provides.

2. *To develop cognitive theory to support, and assess usability of, methods for geovisualization utilizing advances in dynamic (animated and highly interactive) displays*. One of the key issues here is whether animation actually works as a method for depicting geospatial change and process.

3. *To develop an integrated understanding of metaphors and knowledge schemata in the context of geovisualization interface design*. The goal here is to develop more effective interface metaphors, and to understand the schemata people use in working with metaphors and how these schemata evolve with use.

4. *To understand individual and group differences related to use and usability of geovisualization*. Meeting this challenge will support two complementary goals: to facilitate training in geovisualization use and to develop adaptable geovisualization tools that can be configured to match characteristics of individual users or groups of users.

5. *To extend our perspective on cognitive and usability issues associated with geovisualization to contexts that involve group work*. This challenge raises many specific issues including: to understand the differences between individual and group use of displays, to understand and support differences among individual users, and to develop visual methods that support sharing of and negotiation among different user perspectives.

6. *To determine the contexts within which geovisualization is successful*. There have been repeated claims in geovisualization and visualization publications more generally that visualization facilitates science, decision-making, and education. There have, however, been only limited attempts to determine the situations within which these claims are valid or invalid.

7. *To develop methods and tools that will enable the kinds of cognitive and usability research called for*. Current research paradigms and tools for analysis of empirical data are inadequate to the task for two reasons. First, they have been developed for application to analysis of individuals using static visual depictions to carry out relatively well-defined tasks. Second, they were developed to support tightly controlled laboratory studies that rely exclusively on quantitative forms of evidence and analysis. It is essential that mechanisms are developed to integrate multiple forms of evidence.

Crosscutting Research challenges

There are several research problems that were addressed by more than one agenda team. Of these, we highlight four that we believe are fundamental crosscutting issues, that are particularly challenging, that will require a coordinated multidisciplinary approach, and that have implications well beyond geovisualization.

Crosscutting challenge 1. *To develop the understanding and integrated technologies that make it possible to take advantage of the potential offered by increasingly experiential representation technologies*.

VEs and related technologies are resulting in modes of information access and manipulation that are increasingly experiential, thus increasingly similar to multisensory interaction with the real world. For geovisualization to take advantage of these capabilities, several challenging technical problems must be addressed. Among these are limitations in the model of the real world that most geospatial information technologies incorporate; they generally treat space as 2D or 2.5D (manifolds rather than volumes) and treat change over time as an attribute of space (if at all). Beyond the technical challenges, the existing paradigm for geovisualization is grounded in an assumption that abstraction is essential for achieving insight. Many new representation and interaction technologies incorporate the contrasting assumption that realism is the ideal. Exploring the tension between these two perspectives is a fundamental challenge if we are to take advantage of advancing technology (rather than be taken advantage of by it).

Crosscutting challenge 2. *To develop extensible methods and tools that enable understanding of, and insight to be derived from, the increasingly large and complex geospatial data sets becoming available*.

Although the initial promise of visualization methods was to harness the power of human vision to extract meaning from complex sets of information, the geovisualization methods and tools developed thus far do not scale well to the very large data sets now available. Meeting this challenge will require both advances in geovisualization methods and in the integration of these methods with geocomputational ones (that must also be advanced). The goal is to leverage the advantages of computation for extracting pattern from massive complex data sets and the advantages of human vision and domain knowledge to steer the process and determine whether the patterns uncovered are meaningful. A fundamental issue to be addressed here is that current methods and tools do not support effective representation or encoding of geographic knowledge and meaning; thus knowledge construction using these tools cannot build easily from existing knowledge.

Crosscutting challenge 3. *To develop a new generation of geovisualization methods and tools that support group work.*

Most work with geospatial information requires coordinated effort by groups. However, current geovisualization methods and tools are designed for individual use. Advances in display technologies as well as in telecommunications are making multiuser systems possible – but limited attention has been given thus far to either the technological issues of integrating multiuser capabilities that support same and different-place collaborative geovisualization tools or to the cognitive, social, and usability issues of visual display mediated dialogue (among humans or between human and computer).

Crosscutting challenge 4. *To develop a human-centered approach to geovisualization*.

The goal here is to foster a coordinated approach to geovisualization research that integrates work on technological advances leading toward more powerful and usable tools with work on human spatial cognition and on the potential of visual (and other concrete) representations to enable thinking, learning, problem solving, and decision making. A key issue is to move beyond the current "build and they will come" and "one tool fits all" approaches to geoinformation technology. There is a compelling need to address individual and group differences and to develop both the theory and practice needed to support universal access and usability for geospatial data and, at the same time, enable greater personalization of geovisualization tools to meet both task and user needs.

Recommendations for action:

Above, we summarize the integrated set of geovisualization research challenges delineated through this international interdisciplinary effort. The agenda teams, in addition to addressing the research challenges directly, also considered the equally hard problem of making progress toward meeting the challenges. It is clear that the problems identified are complex ones, demanding a concerted effort by a large community of researchers addressing the problems from multiple linked perspectives; thus, cartographers cannot address these challenges alone.

Here, we outline recommendations for actions that individuals, organizations, and groups of organizations can take in order to meet the challenges. Recommendations are divided into two sections. The first relates to meeting the challenges directly. The second focuses on developing the broader and deeper community of scientists that will be required to undertake and extend the work.

To address the research challenges directly and coherently:

Emphasis should be placed on fundamental, crosscutting problems, solutions to which will have broad impacts for both science and society.

Substantial advances have occurred over the past decade in both visualization technologies and their application. Those advances, however, have been idiosyncratic, often driven by the technology and circumstances for application. Three specific actions are recommended here. **First**, attention should be directed to developing a coherent perspective on geovisualization that emphasizes theory development and enables generalization of principles and practice. **Second**, priority should be given to cross-cutting problems because their solution will have broad impact beyond, as well as within, geovisualization. **Third**, addressing the complexity of these problems will require coordinated effort by teams of researchers (rather than individuals working alone, as has been typical).

Mechanisms are needed to enable multidisciplinary and international collaborative research.

Most challenges outlined are multifaceted ones, requiring multidisciplinary perspectives Three specific actions are recommended here. **First**, at the individual level, we need more scientists committed to multidisciplinary research. **Second**, since most universities and research laboratories remain organized by discipline, sustaining multidisciplinary collaboration requires a concerted effort by both national and international professional organizations and research support institutions to initiate and sustain multidisciplinary activities (with support for both research and research infrastructure needed). **Third**, such support needs to be matched with appropriate valuation of multidisciplinary research within systems for reward/recognition in government and industry research laboratories and in universities.

Governments are active generators of geospatial data, with large national differences in kinds of data collected, standards for collection and exchange, and typical applications. For advanced geovisualization methods to handle these differences, a recommended action is for national research support institutions to coordinate initiatives and develop mechanisms that make it easier for projects involving international collaborators to be supported.

Multidisciplinary and international collaborations both involve work at a distance. Two actions are recommended to facilitate this work. **First**, some of the effort directed toward the challenges of collaborative geovisualization should address the particular problems of international collaboration (problems that involve differences in technology, language, and culture). **Second**, rapid transfer of advances in collaborative methods and tools to the wider research community should be facilitated.

To foster a capable and integrated science and engineering community and associated infrastructure that are essential to meeting the challenges:

The number of scientists and engineers who are prepared to contribute to the complex challenges delineated must be increased.

An insufficient number of scientists and engineers are prepared to conduct cutting-edge research in geovisualization and its integration with other aspects of geographic information science, ViSC, and related domains.

In the **short term** (the next 1-5 years), one of the most effective ways to fill this expertise gap is through creation of Post Doctoral research positions affiliated with key programs in Universities and Government research laboratories where geovisualization research is already underway. Such support might come through research agency initiatives that give priority to Post Doctoral researcher positions or through Post Doctoral fellowships (supported directly by research foundations, federal government agencies, and/or universities).

For the **medium term** (the next 3-8 years), University programs should be developed or expanded to focus on preparing the next generation of scientists to address the challenges delineated, and to identify the challenges beyond. In many countries, existing cartography programs offer a base on which to build. They include faculty with considerable expertise in both human-display interaction (from both a cognitive and usability perspective) as well as in design of computer mapping environments, distributed cartographic databases, web delivery of maps, analytical methods, and related areas. In such cases, modest investments could yield a substantial return.

Shared (multidisciplinary and international) understanding of challenges, and approaches to meeting them, must be fostered.

As part of their efforts, each agenda team conducted an extensive review of literature in a wide array of disciplines. This process made it clear that too little exchange of ideas occurs across disciplines working on related problems, with multiple sets of largely separate literature having few or no cross citations. Three actions are recommended.

First, individual scientists should take greater advantage of available electronic publications to identify and stay informed about complementary research in other disciplines. **Second**, organizations should continue to improve access to scientific publications, not only by facilitating access to digital libraries, but also by promoting research that increases the success of search methods in retrieving relevant scientific information. Information visualization that makes use of the concept of *spatialization* has much to offer here. **Third**, workshops should be supported to bring individuals with varied disciplinary perspectives together to discuss research questions and approaches to addressing them in detail. Many applications of geovisualization technologies are to problems that do not recognize international borders (e.g., environmental change, vector-borne disease). As a result, it is critical that workshops bring together scientists who represent international (as well as multidisciplinary) perspectives.

Summary

Many pressing problems facing science and society are inherently geospatial – location matters. The availability of essential geospatial data has increased dramatically over the past decade. Both scientific progress and application of geospatial information to societal needs remains hampered, however, due to the lack of methods for transforming these data into information and for combining information from diverse sources to construct knowledge. Progress requires fundamental breakthroughs in both geovisualization and its integration with other methods for geospatial knowledge construction. The research agenda delineated in this issue is a step toward achieving these breakthroughs. Identifying the challenges is the easy part. Meeting them is unlikely without a commitment to a coordinated approach, by both individuals and organizations in multiple countries.

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Figure Caption

Figure 1. Map Use Cube in which three dimensions, (audience, interaction, and data relations) characterize variables in use of map-based visual display. The evolution of this model of map-based geovisualization can be found in (MacEachren, 1995; MacEachren and Kraak, 1997; Kraak and MacEachren, 1999b).