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<ct>Connecting Geospatial Information to Society through Cyberinfrastructure

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<h1>INTRODUCTION

<t1>Infrastructure refers to the provision of fundamental services that members of society use to sustain modern civilization. The composition of infrastructure has evolved from basic services, such as the roads and water supplies built by the Roman Empire, to other services such as electricity and telephony that were introduced into many societies during thetwentieth century. As computer technologies have advanced, it has become widely accepted that broadband networking and other information technologies have evolved to comprise an important element of infrastructure. Access to this cyberinfrastructure, defined more completely in the following section, has fundamentally changed how computer systems and services are conceived and how the latter are delivered.

<t>The purpose of this chapter is to describe the nature of these changes and the ways that they are manifested in the collection, processing and dissemination of geospatial information. It is important to recognize that these changes in access to technologies, and the technologies themselves, are also altering perspectives of the user community; people are able to conceptualize problems and interact with others in ways that they were unable to only a few years ago. The remainder of the chapter is organized as follows. First, we provide an elaborated definition of cyberinfrastructure and the architectures used to implement it. Then we narrow our focus to a collection of application domains that are germane to geographic information science; these include volunteered geospatial information, wireless and ubiquitous GIS, geospatial web portals and support for virtual organizations. The chapter concludes with an assessment of past

effects of cyberinfrastructure developments and future prospects for transforming human–computer–human interaction within society.

<h1>**CYBERINFRASTRUCTURE**

<t1>During the late 1980s and 1990s, researchers and computer manufacturers began to rethink their conceptualizations of computer systems. Sun Computer, for example, proffered the tagline ‘The network is the computer’ during the 1980s. In the following decade, Larry Smarr and Charlie Catlett (1992) began to develop the concept of a metacomputer, a system of computers that to the user appears to be a single machine. At the turn of the century, these concepts were developed even further. In an introduction to the seminal work on grid computing (Foster and Kesselman, 1999), Smarr (1999) described a vision in which computing would be transformed into another effectively ubiquitous utility that requires an infrastructure to provide service delivery. Similar concepts that are variants on this theme are: utility computing and cloud computing. These and related ideas are now having additional effects, as new services are beginning to expand outside of research labs, into the commercial sector and transforming the way society organizes itself (e.g. social networking services).

<t>The term used to describe the evolving computational and information infrastructure is called cyberinfrastructure (CI). Though this term is unwieldy, it is now widely adopted, largely as a consequence of its promotion by the US National Science Foundation (NSF) (2007) in a series of whitepapers, proposal solicitations and names bestowed on new units of the foundation. CI refers to a coordinated and flexibly-configured collection of heterogeneous networked devices (e.g. high performance computers, sensors, instruments and data repositories), software and human resources that are needed to address computational and data intensive problems in science, engineering and commerce. One additional term is gaining

widespread acceptance in the commercial computing sector; cloud computing (Hayes, 2008; Leavitt, 2009) refers to a group of concepts related to the provision of computing services that bears many similarities to CI.

<h2>Cyberinfrastructure **a**rchitectures

<t1>Cyberinfrastructure is implemented through the use of multiple, interconnected layers of software and hardware with communication protocols that mediate among them. In addition, as conventionally construed, CI refers not only to abstract machine terms, but also to the human resources that support and use the technology. CI architectures are often described in terms of the following abstract layers: hardware, software, middleware and human resources.

<t>The key computational elements of CI are increasingly being transformed into networked assemblages of computers that contain multiple cores. This is taking place because chip manufacturers have reached an economic limit on their ability to improve clock speeds and achieve significant steps in manufacturing processes that lead to shrinking chip form-factors. Instead, manufacturers are turning to architectures that enable them to execute multiple instructions during each time period. This shift towards massive parallelism has recently been recognized by software designers and can best be illustrated by examining what is taking place at Microsoft® and two leading research institutions.

- <bl>Microsoft® has begun a Parallel Computing Initiative and has released a whitepaper that describes a basic change in programming models from single to multiple cores (The Manycore Shift whitepaper). It has also developed and released parallel extensions to .Net, one of their major application development environments.

- University of California, Berkeley and University Illinois, Urbana-Champaign have established Universal Parallel Computing Research Centers (with funding provided by Microsoft® and Intel®). Research at these centers is focused on the development of a complete and widely accessible pipeline of parallel computing technologies from hardware and software to applications. </bl>

<t>In addition to Microsoft® and university research centers, other corporate efforts are particularly notable. In many ways, Google™ defines the current state-of-the-practice: it has developed massive parallel server farms to analyze and monetize the billions of user queries they receive each day. They have also entered into cooperative agreements with IBM® on cloud computing education. Amazon has followed a similar path and now sells computer cycles on demand to customers. These trends in hardware are driving computing costs down to negligible levels, so low that they are, effectively, free (Anderson, 2009).

<h2t>Middleware

<t1>Middleware is specialized software that links disparate systems and data formats to support interoperability. Middleware is also used to coordinate resource allocation and schedule distributed computational tasks. In some instances, middleware is generic and handles routine tasks and widely available data types. In other cases, domain-specific inputs are encountered, thus calling for an additional layer of middleware tailored to that particular domain. Geographic problems have just such a requirement since they must confront the anisotropy that is present in the environment. This lack of geographic uniformity can induce extreme load imbalances among computational resources and services, thus significantly reducing parallel efficiency. Geographic information, therefore, requires the use of a specific type of middleware called geo-middleware (Wang et al., 2002; Wang and Armstrong, 2009).

<t>Other middleware is needed to support different types of geospatial analyses. For example, research on middleware to support large-scale participation in structured processes has been part of the Participatory GIS for Transportation (PGIST) project (Nyerges et al., 2006). Results of the PGIST project demonstrated that a structured discussion tool developed as a combination of structured participation techniques can support larger groups of participants within an analytic-deliberative workflow (Lowry et al., 2008). However, emergent workflow engines are more difficult to design for web services than for integrated server applications.

<h1>**CYBERINFRASTRUCTURE IN APPLICATION**

<t1>CI is being used in numerous applications that link members of society. These social linkages are typically fluid, having flexible rules for joining and leaving and may be driven by political, social or scientific agendas.

<h2>Social **n**etworks

<t1>Computer-mediated social networking services have developed rapidly during the past several years. Starting with SixDegrees in 1977, other social networking services, such as myspace™ (released in 2003) and Facebook (in 2004) and micro-blogging services such as Twitter™ (in 2006) have continued to fuel explosive growth in interpersonal communication (Howard, 2008). CI plays a key role in supporting social interaction in such environments. The mobile web (3G, 4G and WiFi), for example, makes Twitter™ possible. While individual ‘tweets’ are miniscule consumers of bandwidth, cumulatively they form a cacophony. Even more important, however, are trends in which users introduce prodigious amounts of content as they move inexorably towards increased levels of resolution of images and other media. Clearly,

shifts to increased megapixel images and to high-definition television clips will require CI to handle the burden of interactivity.

<t>The rise of social networks is having important effects on personal interactions, information search and the diffusion of ideas (memes), all concepts that are not foreign to geographic researchers. While geographic researchers have written about ‘friends and neighbors effects’, they were hardly anticipating the rise of Facebook friends.

<t>As CI penetrates more deeply into social arrangements and the routine use of geospatial information, it is useful to distinguish several levels of coordination that are supported by the technology. Shirky (2008) describes several on a ladder of such activities; each rung characterized by a higher degree of interaction and agreement:

1. <nl>Sharing – this most basic activity is now well-supported by CI. In the geospatial realm, for example, photos that have been georeferenced are widely shared using technologies such as Flickr®, which is a photo-sharing and content tagging service.
2. The second rung, cooperation, is more difficult since it requires individuals to synchronize with others and often modify their behaviour, to accomplish a goal. In a sense, moving beyond Flickr® with additional meta-data enables the creation of Photosynth™-like applications (Photosynth™ is a web service that allows users to contribute and link photos to produce mosaics and three dimensional scenes). In this case agreement must be shared about how to identify and represent geospatial information so that others can use and interact with it more readily.
3. Collaboration is yet more difficult since it requires, as a basic premise, that no single individual gets ‘credit’ for the production of some good or service. Wikimapia is one

such example where a digital base image is annotated by a large number of individuals who achieve some type of consensus about feature labels.

4 Collective action is the final rung. In this case, requires individuals to commit themselves to a unified effort in which the decision of the group binds the behaviour of individuals. Shirky (2008) cites Hardin’s ‘tragedy of the commons’ as an instance of collective action overcoming individual benefit. </nl>

<t>CI is able to support each of these levels of activity. It is important to note that as we move up levels, increasing amounts of coordinated social interaction and agreement are required. In effect, we must crawl before we walk, walk before we run.

<h2>**Cyberinfrastructure in geospatial information collection**

<t1>Goodchild (2007) describes how enabling technologies have empowered individuals to act as volunteer geospatial data collection agents. The collection of geospatial information by members of society is supported by the ubiquity of mobile computing devices ranging in computing capacity from cell phones, PDAs and tablets, to laptops; such devices enable untethered *in situ* computing (Bennett et al., 2007). When these devices are configured with WiFi (or a different radio technology such as WiMax), they are able to communicate with other devices and serve as metaphorical ‘leaves on a CI tree’. In fact when appropriately configured, a PDA can be used to access powerful computer resources available through the NSF TeraGrid, which is arguably the most capable CI in the world (see Figure 6.1). Geo-middleware supports the linkage of applications to CI resources. Together they are connected through cloud and Grid computing to achieve high performance and distributed computations for ubiquitous access.

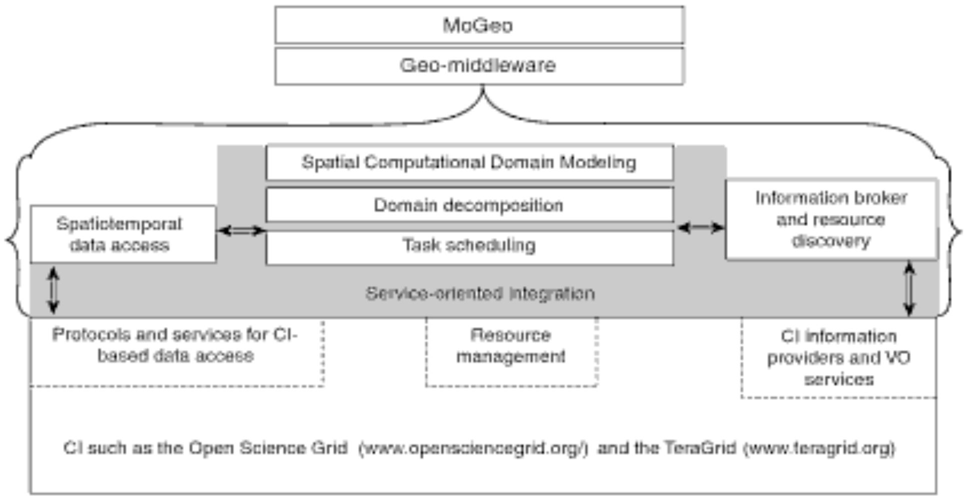

Figure 6.1 Linking spatially aware mobile utilities with CI via geo-middleware

The proliferation of advanced mobile technologies also enables individuals to make contributions to the development of the spatial data infrastructure, often using Web 2.0 software models. Goodchild (2007) describes several key issues in this transformative process:

- <bl>Motivation – people must have a desire to contribute to efforts such as Wikimapia.
- Authority – control over what is added in both the spatial and attribute domains can be contested.
- Access – the digital divide is real and limits what can be added to volunteered geospatial data products. </bl>

<t>Haklay and Weber (2008) describe the process through which individuals contribute spatial information to the OpenStreetMap (OSM) database (see http://www.openstreetmap.org). Unlike other contributed sites (e.g. Wikipedia), OSM brings people together, before they begin data collection, in what are called ‘mapping parties’ that are intended to not only inform contributors

about mapping protocols, but also to foster a sense of community and user group support, thus contributing to both the authority and motivation issues described by Goodchild.

<t>Elwood (2008) explores how new Web 2.0 (web service) technologies associated with volunteered geographic information (VGI) are part of broad shifts in the social and technological processes that support the generation of digital spatial data. She reviews the debates about whether the content and characteristics of geospatial data and the social and political practices that promote their use, are different from previous CI-related GIS developments. She suggests that VGI research could be improved by drawing upon conceptualizations from participatory, feminist and critical GIS research that have emerged from similar foundations.

<h2>**Cyberinfrastructure-enabled information delivery services**

<t1>When mobile devices are equipped with GPS they are able to support the provision of information services that are context-dependent. Such awareness represents a significant departure in the ability of systems to provide information that is tailored to the user in a particular location and context.

<h3>**Cyberinfrastructure** *in data analysis and visualization*

<t1>Data-intensive, large-scale and multi-scale geospatial problems are becoming increasingly important in scientific discovery and decision making in many fields (e.g. ecology, environmental engineering and sciences, geosciences, public health and social sciences). As the size of spatial data and complexity of relevant analysis approaches have increased, spatial data analysis and visualization have become much more dependent on the emerging CI.

<t>Geo-middleware services tailored to the handling of massive spatiotemporal data need to be developed to adapt the generic CI data and visualization services such as the Storage Resource

Broker (SRB) (Rajasekar et al., 2002) and the Replica Location Service (Chervenak et al., 2004). Visualization is an essential element of GIS functions but has been mainly used as a post-processing step in part due to limited visualization resources available in conventional GIS environments. As CI-based visualization hardware resources have become available (e.g. the NSF TeraGrid visualization resources at several supercomputing centers), remote visualization services are able to accommodate on-demand visualization computations. Furthermore, CI-based data and visualization services facilitate interactive visualization for better understanding of intermediate or final data analysis results and, thus, effectively steer data-intensive exploratory analysis.

<h3>*Geoportals*

<t1>A geoportal is a type of web portal used to find and access geographic information (geospatial information) and associated geographic services (e.g. display, editing and analysis) via the Internet (Maguire and Longley, 2005; Goodchild et al., 2007; Wang and Liu, 2009). This approach greatly simplifies access to such services, thus substantially broadening the community of potential users. Geoportals are important for effective use of GIS and are a key element of the emerging spatial data infrastructure.

Virtual Organizations

<t1>CI supports the formation and activities of virtual organizations that address complex problems using geospatial information. A virtual organization (VO) is a '… collection of geographically distributed, functionally and/or culturally diverse entities that are linked by electronic forms of communication and rely on lateral, dynamic relationships for coordination' (DeSanctis and Monge, 1999). Research into VOs has been called out as important within the Cyberinfrastructure Vision for the twenty-first century strategic plan as a '… group of

individuals whose members and resources may be dispersed geographically while the group functions as a coherent unit through the use of CI' (NSF, 2007).

<t>VOs can be particularly useful when public policy problems arise. Such problems contain multiple, often conflicting criteria that must be considered as part of a process of searching for solutions to them. To provide a general perspective, Nyerges and Jankowski (2009) provide a framework for policy decision problems based on four terms 'simple, difficult, complicated and complex'. The four types of decision problems are differentiated in terms of the changes in four components – content, structure, process and context of a problem. When the *content* changes, but structure (relationships), process and context remain the same, then a problem is considered simple. When the *content and structure* (that is relationships) between those elements change, the problem is called difficult. When the content, structure and process components change, the problems can be called difficult. Finally, when all four components are susceptible to change then we can call the problem complex. VOs are particularly suitable to address complex problems, often requiring inputs from many people.

<t>Complex decision problems often involve criteria that span broad areas of expertise and require experts in multiple domains of knowledge. Moreover, complex decision problems may contain aspects that cannot be quantified and easily incorporated into computer-based solution processes. Consequently, decision-making processes are often conducted by panels, committees, boards, councils and other types of deliberative groups. GIS software can be used by deliberative groups (Rinner, 2001; Balram and Dragićević, 2006; Nyerges et al., 2006; Jankowski and Nyerges, 2007) and one branch of the research literature refers to the process as collaborative spatial decision making.

<t>A key element of collaborative spatial decision processes is a focus on the use of maps. In fact, a map forms a central metaphor: the ‘campfire’ around which people gathers to explore and gain an understanding about the geographical characteristics of complex policy problems. But a map in isolation is an insufficient tool. Maps must be linked to other spaces, be transparently interactive and give feedback about consequences of alternative plans in the public realm (Armstrong and Densham, 2008). As shown in Figure 6.2, individual members of a distributed VO can develop their own set of criteria that figure prominently in the course of searching for solutions to a complex problem (e.g. one VO member in this example places a high value on maintaining access by minority groups, as well as minimizing environmental effects). These criteria are realized through their application in models (processed with CI resources); results are then evaluated and placed in a public realm for discussion and debate. CI enables users to analyze complex problems expediently, during the course of a meeting, rather than as multi-hour batch processes that could play no role in deliberation during, say, a one-hour meeting.

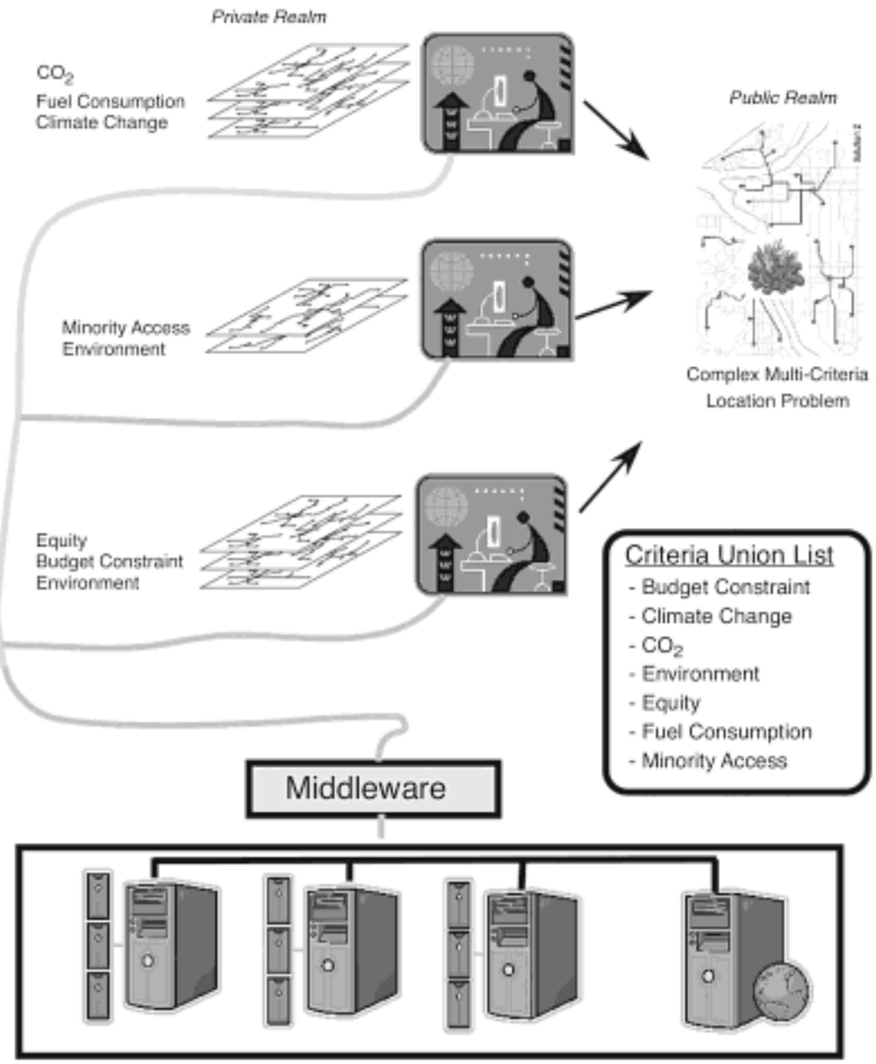

Figure 6.2 A highly stylized representation of CI-enabled collaborative spatial decision making

Maps as analytic devices can be linked to structured online discussions and inform the geographic perspective of analytic-deliberative decision support processes about regional-scale projects (National Research Council, 1996, 2005). Maps at different scales are also advantageous in grounding structured discussions (Aguirre and Nyerges, submitted). Rinner and his colleagues have been working on structured discussion capabilities linked to maps, called argumentation maps, for several years (Rinner, 2001; Kirschner et al., 2003). Argumentation maps provide discussion contributions embedded at the feature locations where those contributions are relevant ‘on the ground’. Using such maps, one should be able to follow a discussion via maps or follow map to map sequences through a conversation.

<t>Looking deeper into the process of collaborative decision making, Jankowski and Nyerges (2001) recognize that at least four, cumulative levels of ‘social interaction’, can be elucidated under the umbrella term of ‘participation’ – *communication, cooperation, coordination and collaboration*. At a basic level of participation, people communicate with each other to exchange ideas as a fundamental process of social interaction. In public decision contexts the traditional forum of a public meeting provides for *communicative* interaction – but only at a most basic level, a drawback to such meetings when ‘truly constructive’ comments are desired. At the next level of social interaction, building on a set of ideas developed through basic communication can be considered to be *cooperative* interaction. Participants in a cooperative activity each agree to make a contribution that can be exchanged, but each can take the results of the interaction away with them and act on the results as they see fit, with no further interaction required. A *coordinated* interaction is one whereby participants agree to cooperate, but in addition they agree to sequence their cooperative activity for mutual, synergistic gain. A *collaborative* interaction is one whereby the participants in a group agree to work on the same task (or subtask) simultaneously or at least with a shared understanding of a situation in a near-simultaneous manner.

<t>One of the recent directions for CI-enabled participatory GIS research is scaling analytic-deliberative processes to very large groups (Nyerges et al., 2006). CI middleware capabilities are needed for language processing in order to establish shared meaning among deliberative contributions at multiple levels of granularity. A formal ontology consisting of shared meaning

terms is needed to scale deliberative discussions. Connections between natural language processing and the mapping of ontologies to computational lexicons like OpenCyc look promising for exploitation. The spatial characteristics of such connections,and those represented using maps, are crucial to the effective design of geo-middleware for user-centric collaborative spatial problem solving based on cyberinfrastructure capabilities (Figure 6.3).

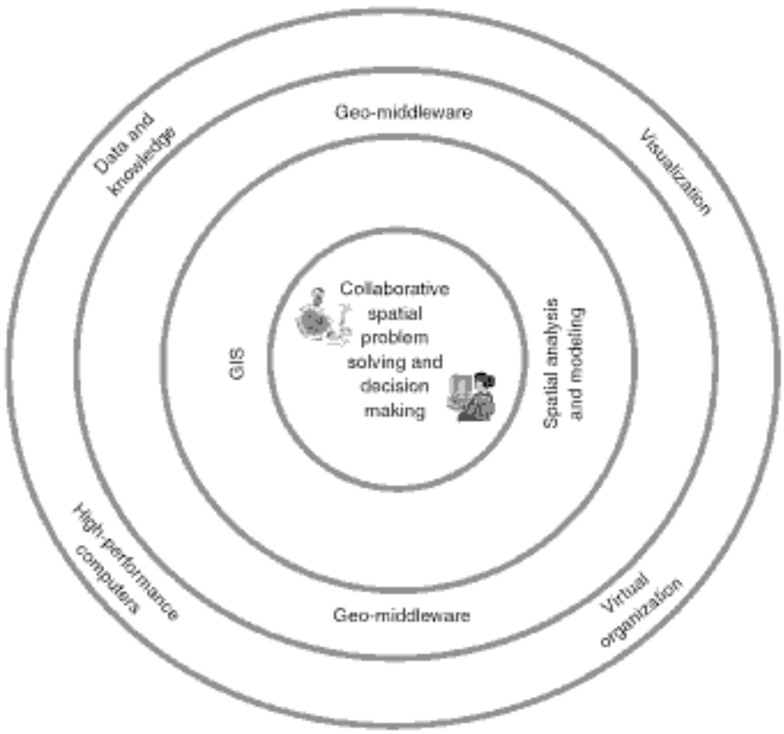

Figure 6.3 Geo-middleware as the bridging layer between major CI capabilities and GIS, spatial analysis and modeling for user-centric collaborative spatial problem solving

<h2>Science Communities

<t1>Cyberinfrastructure in service to both science and society has developed in many scientific domains, such as the iPlant collaborative for the plant science community (http://iplantcollaborative.org), the Geosciences Network (GEON) for the geology and geophysics community (http://www.geongrid.org), the National Ecology Observatory Network (NEON) for terrestrial ecology (http://www.neoninc.org) or the Thematic Real-Time

Environmental Distributed Data Services (THREDDS) for the atmospheric science community and related earth system science research (http://www.unidata.ucar.edu/projects/THREDDS). While it is beyond the scope of this chapter to cover all science communities, one exemplar is that of oceanography and marine resource management, where researchers have been concerned for many decades with the acquisition, management, analysis and publication of geographic data from the world's deep oceans and nearshore/coastal environments. The societal motivation for this is from the standpoint of economics, public safety, public education and regional governance, as well as science. For example, the oceans are home to many fish, birds and mammals, as well as a zone that is critical to coastal economies via sport and commercial fishing and tourism. Data collection and monitoring of fishing grounds is necessary to keep the abundance of commercial species at sustainable levels. Mapping of the seafloor within the territorial seas and Exclusive Economic Zones of the US west coast will greatly improve tsunami inundation modeling, which is critical to protecting life and property in coastal towns. And knowledge of sea surface temperature and wind stress, as well as the chemical and physical structure of shallow depths is needed to track severe storms, to monitor the heat budget of the planet (global warming), as well as to gain an improved understanding of climate systems at a range of scales.

<t>Massive data volumes from the ocean are now available through innovations in remote sensing (both satellite based and *in situ* acoustic), ocean sensor arrays, telemetry tracking of marine animals, submersibles, remotely operated vehicles, hydrodynamic models and other emerging data collection techniques. These observations have been added to the information data streams now available to answer research questions in basic science and exploration and applications in ocean protection, preservation and management. The three-dimensional nature of

the marine domain, the temporal dynamics of marine processes and the hierarchical interconnectedness of marine systems grossly increase the complexity of effective spatial solutions to these questions (e.g. Wright and Halpin, 2005; Baker and Chandler, 2008). Approaches to studying and managing the oceans are evolving as ocean observing systems with an emphasis on real-time collection, discovery and dissemination of data for hurricane tracking and storm surge prediction, global climate change monitoring and general environmental protection. All of these approaches have geographic space as a crucial component (e.g. Graybeal et al., 2005; Wright, 2005; Arrot et al., 2006; Gomes et al., 2007) and the choice of where to locate the arrays is of crucial importance. These observing systems are based on a conceptual infrastructure design for information management and system control that allows access to the real-time data and assimilation of that data into predictive models, while integrating with deep archives of legacy data. A central architectural element is a federated data management system, implemented on a continuum from local clusters to a national grid and providing data catalog and repository services to the oceanographic communities (Arrot et al., 2006).

<t>CI for the ocean/coastal realms is emphasizing interoperability as a key requirement for success, where access to data and information become truly universal and translations exist between the terms and understandings as expressed by ocean/coastal biologists, physicists, chemists, geologists, engineers and resource managers (e.g. Helly et al., 2003; Chandler, 2008). As such, semantic interoperability is being designed, developed and evaluated via controlled vocabularies and ontologies, semantic web technologies, system support of machine access in addition to human clients and metadata systems to support automated, accurate, machine-to-machine exchange of information (e.g. Chandler, 2008; Marine Metadata Interoperability,

2009). A growing number of research projects and initiatives in global ocean science are finally seeking to implement CI to serve diverse approaches to science (Baker and Chandler, 2008). For the coast and oceans, it is clear that CI is now crucial, but its use in this challenging environment can also advance the body of knowledge in CI design and architecture in many other application domains.

<h1>**SOCIETAL ISSUES**

<t1>The provision of geospatial information using CI can cause a wide variety of social and economic problems and create opportunities for malicious behaviour. In this section we describe several issues that either have emerged or are likely to emerge in the not-too-distant future.

<h2>Access

<t1>Differential use of geospatial information through CI creates imbalances among social and economic groups. This can take place not only as a consequence of the ‘digital divide’, which is often construed as an access to hardware issue, but may also have its genesis in the ability of some groups to use geospatial information to marshal persuasive arguments. With respect to physical access, a large proportion of individuals on this planet have no Internet connectivity. While there are efforts to change this (the so-called US$100 laptop, e.g. Kraemer et al. 2009), differentials in information access will remain in place. The issue of conceptual access is also largely, but not exclusively, rooted in class and income differentials, which also often have a racial component.

<h2>Privacy

<t1>Access to high-resolution geospatial information can also enable individuals to compromise certain aspects of privacy. For example, it is relatively easy to link disparate databases using geographic identifiers. Such linked data can yield insights into behaviours that are not otherwise

available. Geospatial information can also be used to transform information in ways that might make individuals uncomfortable. For example, an inverse geocoding transformation can turn relatively anonymous pin maps into address lists that can then be linked with other databases (Armstrong and Ruggles, 2005).

<t>Dobson (2009) expresses similar concerns about a study conducted by computer scientists at a US university whose observations about the daily movements of humans are potentially important for improving public safety and homeland security, as well as the forecasting of infectious disease spread, traffic flows and other diffusion processes related to human mobility (Gonzáles et al., 2008). However, their observations were based on the cell phone records of individuals who had not given their consent and whose identities had not been masked. This and other examples (Lane, 2003; National Research Council, 2007a, 2007b, 2008; VanWey et al., 2005; Bertino et al., 2008;) underscore the difficulties faced by researchers today.

<h2>Quality

<t1>In the past, the creation and dissemination of geospatial information was dominated by government agencies and large corporations. These organizations imposed controls on the type, quantity and quality of information that was contained in their products. As the amount of content contained in online repositories is increasingly contributed by individuals with unknown skill levels, quality can become suspect. As a consequence any use of the information in analyses may contain large errors.

<h2t>Aggression

<t1>The quality issues described in the previous section are assumed to be the result of errors of omission and accidental errors of commission. However, it is well within the realm of

possibilities that intentional errors could be introduced into geospatial information in much the way that revisionist and even malicious Wikipedia entries occur.

<h2>Piracy

<t1>Contributed or volunteered geospatial information is given freely for the idealized common good. Considerable effort may be expended on such contributions. And the results can be a rich and useful compendium. It may become so rich and useful, however, that individuals would be motivated to appropriate and repackage it for commercial or other uses. Such ‘piracy’ is hardly new. It was widely rumored, for example, that commercial map companies would introduce intentional small ‘signature’ errors into their products to enable them to detect whether a competitor or user had copied their intellectual property without permission.

<h2>**Educational shallowness**

<t1>Just as the exclusive use of Wikipedia is sometimes viewed as the gold standard of shoddy research, online access to geospatial information may limit the pursuit of richer, more difficult to obtain or use, resources. And what of the quality of VGI? Studies such as Flanagin and Metzger (2008) assess the level of trust users have now in, for example, Wikipedia, Google Earth™ and Citizendium and develop new analyses and rubrics for geographic training and education of novices by experts.

<h1>**CONCLUSION**

<t1>CI can be characterized as a disruptive technology, in the sense that it is providing a new mode of access to geospatial information and processing services. Moving away from the single desktop model of computing, CI uses distributed processing models supported by high speed networks and specialized middleware to expand the range of capabilities that are available to users. CI moves beyond the capabilities that were provided by web geospatial applications

which mainly altered information at the presentation level. With the development of CI and associated software environments, information now flows bi-directionally. Applications for public decision support are of this nature. They offer opportunity for more meaningful participation than traditional forms of public participation. The big challenge is how to scale out that participation to thousands of people, while at the same time scale high to increase technical competence for those involved (Aguirre and Nyerges, submitted).

<t>Beyond these applications are those that provide users with increased control over content and presentation. We might think of this as the next step beyond Web 2.0 applications. This inversion of Web Services has enabled the rise of contributed geospatial information and has diminished the centralized control of geospatial information and services by command bureaucracies. The rise of two-way completely distributed web apps, however, raises both epistemic and ontological problems.

<t>Despite such problems, large investments, in both the public and private sectors are being made to support the development of CI: NSF, Department of Energy and National Institutes of Health among other federal funding agencies are providing millions of dollars of research funding each year. In the private sector, major IT and e-commerce companies are also vigorously pursuing the design, development and adoption of CI-based access to information and services. Given these substantial investments, there are abundant opportunities for research and development in the general area of geospatial CI and its role in society. Geographical researchers have unique perspectives that can be used to contribute in many ways, ranging from critical theory to GIScience approaches to distributed geographic information analysis. A particularly promising avenue of research lies in the use of CI to address complex geospatial problems by members of virtual organizations.

<Ref>References

<ref_list>Aguirre R. and Nyerges, T. (submitted) ‘Geovisual evaluation of public participation in decision making: The 4D grapevine technique’, *Journal of Visual Languages and Computing.*

Anderson, C. (2009) *Free: The Future of a Radical Price*. New York: Hyperion.

Armstrong, M.P. and Densham, P.J. (2008) ‘Cartographic support for locational problem-solving by groups’, *International Journal of Geographical Information Science,* 22 (7): 721–749.

Armstrong, M.P and Ruggles, A. (2005) ‘Geographic information technologies and personal privacy’, *Cartographica* 40(4): 63–73.

Arrot, M., Chave, A., Graybeal, J., Kruieger, I., Guillemot, E. and Pirotte, B. (2006) *Ocean Research Interactive Observatory Networks (ORION) Cyberinfrastructure Concept Architecture*. Available online at http://orionprogram.org/advisory/committees/ciarch/ (accessed 16 June 2009).

Baker, K.S. and Chandler, C.L. (2008) ‘Enabling long-term oceanographic research: Changing data practices, information management strategies and informatics’, *Deep-Sea Res. II*, *55*, doi:10.1016/j.dsr2.2008.05.009.

Balram, S. and Dragićević, S. (eds) (2006) *Collaborative Geographic Information Systems.* Hershey, PA: Idea Publishing.

Bertino, E., Thuraisingham, B., Gertz, M. and Damiani, M.L. (2008) ‘Security and privacy for geospatial data: Concepts and research directions’, *SPRINGL ’08: Proceedings of the SIGSPATIAL ACM GIS 2008 International Workshop on Security and Privacy in GIS and LBS.*

New York: Association for Computing Machinery. pp. 6–19.

Bennett, D.A., Armstrong, M.P. and Mount, J.D. (2007) 'MoGeo: A location-based educational service'. In G. Gartner, W. Cartwright and M. P. Peterson (eds), *Lecture Notes in Geoinformation and Cartography: Location Based Services and Telecartography*. New York: Springer. pp. 493–508.

Catlett, C. and Smarr, L. (1992) 'Metacomputing', *Communications of the Association for Computing Machinery,* 35(6): 45–52.

Chandler, C. (2008) 'Introduction to interoperability', *Proceedings of the 2008 Ocean Observing Systems Interoperability Planning Workshop*. Huntsville: Alabama. Available online at http://marinemetadata.org/workshops/oosinterop2008/oosip/oosipoverview/ (accessed 16 June 2009).

Chervenak, A.L., Palavalli, N., Bharathi, S., Kesselman, C. and Schwartzkopf, R. (2004) 'Performance and scalability of a replica location service', *Proceedings of the 13th IEEE International Symposium on High Performance Distributed Computing.* IEEE Computer Society.

Desanctis, G. and Monge, P. (1999) 'Communication processes for virtual organizations', *Organization Science,* 10(6): 693–703.

Dobson, J.E. (2009) 'Big Brother has evolved', *Nature,* 458(7241): 963.

Elwood, S. (2008) 'Volunteered geographic information: future research directions motivated by critical, participatory, and feminist GIS', *GeoJournal*, 72 (3/4): 173–183.

Flanagin, A.J. and Metzger, M.J. (2008) 'The credibility of volunteered geographic information', *GeoJournal*, 72: 137–148.

Foster, I. and Kesselman, C. (eds) (1999) *The Grid: Blueprint for a New Computing Infrastructure*. San Francisco, CA: Morgan Kaufman.

Gomes, K.J., Graybeal, J. and O'Reilly, T.C. (2007) 'Data management issues in operational ocean observatories', *Sea Technology,* 48(5): 17–20.

González, M.C., Hidalgo, C.A. and Barabási, A.L. (2008) 'Understanding individual human mobility patterns', *Nature,* 453, 779–782.

http://www.nature.com/nature/journal/v453/n7196/full/nature06958.html – a1#a1

Goodchild, M.F., Fu, P. and Rich, P.M. (2007) 'Geographic information sharing: The case of the Geospatial One-Stop portal', *Annals of the Association of American Geographers,* 97 (2): 250–266.

Goodchild, M.F. (2007) 'Citizens as sensors: The world of volunteered geography', *GeoJournal,* 69: 211–221.

Graybeal, J., Bellingham J.G. and Chavez, F.P. (2005) 'Data systems for ocean observation programs', *Sea Technology,* 46(9): 23–24, 26.

Haklay, M. and Weber, P. (2008) 'OpenStreetMap: User-generated street maps', *IEEE Pervasive Computing*, 7(4): 12–8.

Hayes, B. (2008) 'Cloud computing', *Communications of the Association for Computing Machinery*, 51(7): 9–10.

Helly, J., Staudigel, H. and Koppers, A. (2003) 'Scalable models of data sharing in earth sciences', *Geochemistry Geophysics Geosystems*, 4(1): 1010, doi: 10.1029/2002GC000318.

Howard, B. (2008) 'Analyzing online social networks', *Communications of the ACM*, 11 (8): 14–16.

Jankowski, P. and Nyerges, T. (2001) *Geographic Information Systems for Group Decision Making*. New York: Taylor & Francis.

Jankowski, P. and Nyerges, T. (2007) 'GIS and participatory decision making'. In John Wilson and Stuart Fotheringham (eds), *Handbook of Geographic Information Science*. Blackwell. chapter 27.

Kirschner, P.A., Shum, J.B. and Carr, C.S. (ed.) (2003) *Visualizing Argumentation: Software Tools for Collaborative and Educational Sense-Making*. New York: Springer.

Kraemer, K.L., Dedrick, J. and Sharma, P. (2009) 'One laptop per child: Vision vs. reality', *Communications of the Association for Computing Machinery*, 52(6): 66–73.

Lane, J. (2003) *Key Issues in Confidentiality Research: Results of an NSF Workshop*. Washington, D.C: National Science Foundation. http://www.nsf.gov/sbe/ses/mms/nsfworkshop_summary1.pdf (accessed 16 June 2009).

Leavitt, N. (2009) 'Is cloud computing really ready for prime time?', *IEEE Computer*, 42(1): 15–20.

Lowry, M., Nyerges, T. and Rutherford, G.S. (2008) 'An internet portal for large group participation in transportation programming decisions'**,** *Transportation Research Record***,** Publication 2077, National Academy of Sciences, Washington, D.C.

Maguire, D.J. and Longley, P.A. (2005) 'The emergence of geoportals and their role in spatial data infrastructures', *Computers, Environment and Urban Systems,* 29: 3–14.

Marine Metadata Interoperability project, hosted by Monterey Bay Aquarium Research Institute and Woods Hole Oceanographic Institution. http://marinemetadata.org (accessed 16 June 2009).

National Research Council (1996) *Understanding Risk: Informing Decisions in a Democratic Society.* Washington, DC: The National Academies Press.

National Research Council (2005) *Decision Making for the Environment: Social and Behavioral Science Research Priorities*. Washington, DC: The National Academies Press.

National Research Council (2007a) 'Engaging privacy and information technology in a digital age'. In J. Waldo, H.S. Lin and L.I. Millett (eds), *Committee on Privacy in the Information Age, Computer Science and Telecommunications Board, Division of Engineering and Physical Sciences.* Washington, DC: The National Academies Press.

National Research Council (2007b) 'Putting people on the map: Protecting confidentiality with linked social-spatial data'. In M. P. Gutmann and P. C. Stern (eds), *Panel on Confidentiality Issues Arising from the Integration of Remotely Sensed and Self-Identifying Data, Committee on the Human Dimensions of Global Change.* Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

National Research Council (2008) 'Protecting individual privacy in the struggle against terrorists: A framework for assessment'. In W. J. Perry and C. M. Vest (eds), *Committee on Technical and Privacy Dimensions of Information for Terrorism Prevention and Other National Goals.* Computer Science and Telecommunications Board, Division of Engineering and Physical Sciences. Washington, DC: The National Academies Press.

National Science Foundation (2007) *Cyberinfrastructure Vision for 21st Century Discovery*. http://www.nsf.gov/pubs/2007/nsf0728/nsf0728.pdf (accessed January 2009).

Nyerges, T. and Jankowski, P. (2009) *Regional and Urban GIS: A Decision Support Approach*. New York: Guilford Press.

Nyerges, T., Ramsey, K. and Wilson, M. (2006) 'Design considerations for an internet portal to support public participation in transportation improvement decision making'. In S. Balram and

S. Dragićević (eds), *Collaborative Geographic Information Systems.* Hershey, PA: Idea Publishing. pp. 208–230.

Rajasekar, A., Wan, M. and Moore, R. (2002) 'MySRB and SRB: Components of a data grid', *Proceedings of the 11th IEEE International Symposium on High Performance Distributed Computing.* IEEE Computer Society.

Rinner, C. (2001) 'Argumentation maps: GIS based discussion support for on-line planning', *Environment and Planning B: Planning and Design,* 28: 847–863.

Shirky, C. (2008) *Here Comes Everybody: The Power of Organizing without Organizations*. New York: Penguin.

Smarr, L. (1999) 'Grids in context'. In I. Foster and C. Kesselman (eds), *The Grid: Blueprint for a New Computing Infrastructure*. San Francisco, CA: Morgan Kaufman. pp. 1–14.

VanWey, L.K., Rindfuss, R.R., Gutmann, M.P., Entwisle, B. and Balk, D.L. (2005) 'Confidentiality and spatially explicit data: Concerns and challenges', *Proceedings of the National Academy of Sciences*, 102(43): 15337–15342.

Wang, S. and Armstrong, M.P. (2009) 'A theoretical approach to the use of cyberinfrastructure in geographical analysis', *International Journal of Geographical Information Science*, 23(2): 169–193.

Wang, S., Armstrong, M.P. and Bennett, D.A. (2002) 'Conceptual basics of middleware design to support grid computing of geographic information', *Proceedings of 2nd International Conference on Geographic Information Science*. 25–28 September. Boulder: CO, USA. pp. 197–200.

Wang, S. and Liu, Y. (2009) 'TeraGrid GIScience gateway: Bridging cyberinfrastructure and GIScience', *International Journal of Geographical Information Science*, 23(5): 631–656.

Wright, D.J. (2005) ‘Data management a top priority?’, *Sea Technology*, 46(2): 93.

Wright, D.J. and Halpin, P.N. (2005) ‘Spatial reasoning for terra incognita: Progress and grand challenges of marine GIS’. In D. J. Wright and A. J. Scholz (eds), *Place Matters: Geospatial Tools for Marine Science, Conservation and Management in the Pacific Northwest*. Corvallis, OR: Oregon State University Press. pp. 273–287.