GeoJournal (2010) 75:3–13
DOI 10.1007/s10708-010-9340-3

Toward critical spatial thinking in the social sciences and humanities

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Published online: 30 January 2010

Abstract The integration of geographically referenced information into the conceptual frameworks and applied uses of the social sciences and humanities has been an ongoing process over the past few centuries. It has gained momentum in recent decades with advances in technologies for computation and visualization and with the arrival of new data sources. This article begins with an overview of this transition, and argues that the spatial integration of information resources and the cross-disciplinary sharing of analysis and representation methodologies are important forces for the integration of scientific and artistic expression, and that they draw on core concepts in spatial (and spatio-temporal) thinking. We do not suggest that this is akin to prior concepts of unified knowledge systems, but we do maintain that the boundaries to knowledge transfer are disintegrating and that our abilities in problem solving for purposes of artistic expression and scientific development are enhanced through spatial perspectives. Moreover, approaches to education at all levels must recognize the need to impart proficiency in the critical and efficient application of these fundamental spatial concepts, if students and researchers are to make use of expanding access to a broadening range of spatialized information and data processing technologies.

Keywords Spatial concepts · Spatial integration · Spatial thinking · Spatio-temporal knowledge systems

Introduction

Why is it that spatial intelligence has not received the same level of interest in education as reading, written communication, and computational reasoning? After all, society has always understood that location and geographical patterns of resource distributions and markets can influence strategic planning in commerce and politics. At a more mundane level, being able to navigate from one place to another is recognized as critical both to the daily survival of individuals at local levels and to the geopolitical fortunes of nations and empires. Perhaps these abilities are instinctive, or acquired at such an early age that they require no attention from our educational system. Or, are society and its approach to education failing to nurture a fundamental element of human intelligence?

What we now take for granted as the known distribution of land and water on the Earth's surface emerged slowly over centuries as the result of huge investments in navies and expeditions, development of new tools (spatial technologies), compilations of observations, and working from the known through

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extrapolation and interpolation to approximations of expected distributions. This process has demonstrated a high level of commitment to the development and application of spatial reasoning. But beyond this level of global abstraction lie such topics as the hidden dimensions of human settlement patterns, the correlations that might exist between physical environmental factors and human health, or the prediction of human migratory flows over time. In these settings, the applications of spatial reasoning take a different turn, combining, for example, the need for a census or other detailed geo-referenced assemblies of information about a vast array of phenomena with the recognition that geographical maps and spatial statistics can become descriptive as well as analytic tools, and that they lie at the heart both of scientific investigation and discovery and of creative achievements in the arts and humanities.

Profound accomplishments have emerged through spatial thinking about a large number of applications over the past few centuries. Yet, the systematic development of computational tools for handling spatial data began only in the 1960s, and today GIS (geographic information systems) and software for image processing, pattern recognition, and scientific visualization are in widespread use throughout many disciplines. Functions for the manipulation, analysis, and modeling of spatial data are now available in standard statistical and mathematical packages. The introduction of the Web in the early 1990s helped to make digital images readily sharable, and pictures of the brain, of Earth from space, and of space from Earth are now important tools in the neuro-, Earth, and astronomical sciences, respectively. GPS and GIS have become ubiquitous tools in many career fields and in everyday life. Previously, the complexity of formal GIS made it difficult to use before the high-school level, but now students at the elementary level can access some of its functions through such services as Google Earth.

Spatial turns in the sciences and social sciences

Space appears to have found new theoretical significance in many disciplines in recent years. For example, in ecology, Tilman and Kareiva (1997) observe that, "although the world is unavoidably spatial, and each organism is a discrete entity that exists and interacts only with its immediate neighborhood, these realities have long been ignored by most ecologists because they greatly complicate field research and modeling". Dealing with such complications has been the subject over the past two decades of research efforts in several disciplines, including statistics, computer science, and geography. Reflecting the fundamental nature of such issues to computer science, the Association for Computing Machinery approved a new Special Interest Group (SIGSPATIAL) in 2009 on "issues related to the acquisition, management, and processing of spatially-related information."

The flow of information from a host of sensors has grown exponentially in recent years to the point where the lead editorial in *Nature* (Anonymous 2008) urged that *all* observations in the environmental sciences be georeferenced. The easy availability of GPS enables spatial analysis and modeling, and addresses the issues of importance to the sciences and humanities that are posed by the vast legacy of museum and herbarium artifacts for which the location of collection is poorly recorded (Liu et al. in press). The ability to reason about, and to draw inferences from spatial pattern has been critical in numerous breakthroughs in epidemiology, starting perhaps with Snow's mid-nineteenth century work on cholera (Johnson 2006). Scholten et al. (2009) provide a recent overview of how location has achieved central significance in science owing to developments and applications of geospatial technologies.

Coupled with the development of new exploratory tools for mapping and analysis, the momentum of applications in the social sciences has been especially evident, documented as a *spatial turn* in recent compilations of research by Anselin et al. (2004) on applications of spatial econometrics; and by Goodchild and Janelle (2004), Scholten et al. (2009), and Nyerges et al. (in press) on broad-based applications of spatial methodologies in a range of social sciences. Paul Krugman's 2008 Nobel Prize in Economics, for example, was based in part on his reintroduction of the importance of location in understanding economic activity (Krugman 1991), attesting to the significant potential that spatial understanding adds to traditional approaches to the sciences and social sciences. Contemporary advances in the uses of spatial reasoning in demography and sociology are profiled by Castro (2007), Voss et al. (2006); and

Voss (2007). Cromley and McLafferty (2002) explore applications of GIS in public health research; and the journal *Political Analysis* released a special issue on spatial methods in political science (Vol 10(3), 2002).

Spatial thinking in the humanities

In the humanities, the Electronic Cultural Atlas Initiative (http://www.ecai.org) has for the past decade been a significant agent of dissemination of spatial thinking, bringing together scholars from such disciplines as archaeology, anthropology, history, and religious studies, and from library and museum archives, to map human cultural heritage and to document the role of place in society. Another equally important demonstration in the humanities of the value of spatial perspective is the Spatial History Project at Stanford University (see http://www.stanford.edu/group/spatialhistory). It brings together scholars at the intersection of geography and history who use GIS in their research, but also focuses on the harvesting of large datasets of maps, images, and texts, and their integration to create dynamic, digital visualizations of change over space and time. The Social Science History Association (http://www.ssha.org) also regularly features sessions on spatial perspectives in its conferences.

Highlighting the enhanced recent attention to spatial dimensions of scholarship in the humanities, two important conferences took place in 2009—the *Spatial Technologies and Humanities Conference*, sponsored and hosted by the Scholarly Communication Institute (SCI) at the University of Virginia in Charlottesville, and the *GIS in the Humanities and Social Sciences International Conference 2009* (GISHSS), hosted by the Research Center for Humanities and Social Sciences of Academia Sinica, in Taipei, with support from Queen's University Belfast, and Indiana University-Purdue University at Indianapolis.

The SCI conference resulted in an online report (Rumsey 2009) that clearly articulates on potential applications of geospatial and mapping technologies, concept mapping, and library technologies to create virtual worlds for scholarly communication in the arts and humanities. The conference brought together scholars and academic leaders from different disciplines, academic libraries, higher education, and information technologies to explore the full life-cycle of scholarly communication, from research and discovery to analysis, presentation, dissemination, and persistent access.

The SCI report addresses the importance of a space–time perspective and argumentation in the interpretations of spatial data, acknowledging that interest in digital forms of space–time patterns has grown as the accessibility of location-aware devices and services has proliferated. Mapping services on the Web, especially Google Earth, have become popular gateways for visualizations of information. Nonetheless, as noted by Jessop (2007), although information about place and location is an essential part of research in the humanities, sophisticated analytical programs such as GIS remain slow to accommode the specific concerns of the humanities, a theme developed more explicitly with respect to history by Boonstra (2009). In general, the "… humanities disciplines most influenced by the linguistic and visual turns in scholarship over the past few decades have not given priority to critical spatial reasoning" (Rumsey 2009, p. 4), possibly reflecting the importance attached to both the real and the imaginary in human culture, to concern for the qualitative attributes of place, and to representations of nonwestern perspectives on space and time. Interestingly, geographers at the SCI conference noted a convergence of interest with the humanities, both in examining how subjective and qualitative elements of spatial patterns are represented within current GIS applications, and in recognizing the need for ways to reflect uncertainty and ambiguity.

The GISHSS conference was similarly focused on the integration of cultural and social nuance in the humanities and social sciences with GIS and other spatial analytic frameworks. Harris (2009) proposed a general conceptualization of the role of GIS within spatial humanities, while Gregory (2009) described how both quantitative and qualitative approaches might be integrated within GIS for interpreting literature and news reports from prior eras. Ayers (2009) illustrated the potential of dynamic mapping for interpreting historical changes, and Fotheringham (2009) demonstrated how advanced spatial-analytic methods contribute to the understanding of population dynamics. Janelle (2009) explored trends and ambiguities in the space–time documentation of human behavior and social organization. The importance of spatial thinking in the social sciences was addressed by Phoenix (2009), while Goodchild (2009) made the case that critical spatial thinking should be a central theme in education for a world where information is increasingly seen through geographical filters, is broadly accessibly to the general population, and is both generated and disseminated voluntarily through digital media.

Spatially integrative knowledge systems

Although disciplines have demonstrated and continue to play a critical role in the advancement of scientific and humanistic understanding, the SCI and GISHSS conferences may represent the seeds of a fundamental shift from disciplinary to integrative knowledge systems. Examples of integrative knowledge systems arise from the application of concepts of *space* and *place*, and *space* and *time*, having near universal relevance to scholarship in diverse knowledge domains, with the focus here on their meaning in the humanities and social sciences.

Integration through concepts of space and place

Throughout our discussion we have seen instances of how space and place are important elements in social science and humanities interpretations of human well-being and changing environments. But a recently announced White House *place-based initiative* (Orszag et al. 2009) ups attention to the importance of place understanding in formulating sound policy development and plan implementation. The initiative advocates place-based policies to leverage "… investments by focusing resources in targeted places and drawing on the compounding effect of well-coordinated action…" to influence the development of rural and metropolitan areas and their "… function as places to live, work, operate a business, preserve heritage, and more."

Cummins et al. (2007) provide a case for place-based policy formulation in health research and health-policy interventions. Arguing that conventional approaches underestimate the contribution of place to disease risk, they call for relational views to help identify reciprocal relationships between people and place. Matthews (2008) reinforces this view, documenting how neighborhood context is an important conditioner of human well-being. Indeed, place has emerged as an important contextual framework for considering a number of critical societal issues, noted for example by Janelle and Hodge (2000) in *Information, Place, and Cyberspace: Issues in Accessibility* or in the recent *Place, Health, and Equity Conference* hosted by the University of Washington (http://courses.washington.edu/phequity/Equity_annoucement_combo.pdf). Whereas the former drew attention to fundamental linkages between virtual and geographical processes, the latter was grounded in "… place as a social context that is deeply connected to larger patterns of social advantage and disadvantage [and that] calls for multifaceted conceptions of place as well as methods that can flexibly encompass geographic location, material form, the meaning-making of diverse groups, and the dynamics of rapidly changing rural and urban environments."

Representation and search

There are, of course, other aspects of space and place that link to the research practices of scholars in the social sciences and humanities. For example, owing to the multidimensional nature of spatial data, there are technical issues regarding search for digital place-based information. The Alexandria Digital Library (ADL), developed at the University of California Santa Barbara (UCSB), was one of the first remotely accessible libraries to support indexing and search across massive repositories of spatial data. The ADL contributed to the development of indexing structures for large-scale retrieval and to the development of privacy-secure methods for querying public spatial data. Further advances in the science of search will entail resolving problems in managing large volumes of data, tracking data provenance (a key issue when spatial data are shared and processed across scientific communities), understanding the semantics of spatial data, and designing methods for achieving interoperability across diverse information communities (Goodchild et al. 1999).

Volunteered geographic information

From the perspective of the humanities and social sciences, the Web itself is seen as searchable repository of potential data sources, some of a traditional nature (e.g., images, works of art, literature, speeches, maps, census data, or newspapers), and others of a more informal nature, such as the user-generated content found on social network sites. Today there are opportunities for anyone to contribute resources (pictures, blogs, etc.) that are automatically geo-referenced by latitude and longitude and available to be retrieved by others. Goodchild (2007) has termed the result volunteered geographic information (VGI). Current research on VGI is featured in a special *GeoJournal* issue (Elwood 2008), which explored questions surrounding the uses of such repositories as keys to social process, environmental understanding, and place-based knowledge. This followed a late 2007 research workshop that brought together researchers from industry, government, and academia to grapple with the complexities of acquisition, validation, distribution, display, and analysis of VGI data sources, calling attention to both the opportunities and the challenges that confront scholars in their use (http://ncgia.ucsb.edu/projects/vgi/).

Spatialization and visualization

Spatialization refers to the construction of abstract spaces of knowledge that can aid in visualization, pattern detection, and the accumulation of scientific insight (Skupin and Fabrikant, 2003). Thus, things that are not explicitly spatial (e.g., social and kinship networks) may be rendered graphically for spatial visualization. At the 2009 SCI conference, participants recognized that "… there is an unexplored universe of spatial information implicit in existing sources, both digital and analog. When 'liberated' from a static analog medium and made legible to geospatial technologies, a whole new reservoir of information will be available to nourish new fields of inquiry" (p. 3). For example, historians and literary scholars might explore the locational and spatial information embedded in nineteenth century novels, railroad timetables, sound media, or old maps. Another important aspect of this is the issue of *respatialization*, defined as the transformation of spatially referenced data from their original geographic representation to an alternative geographic framework (Goodchild et al. 1993). For example, data gathered for politically defined units such as counties, states or provinces, or nations are typically based on a particular spatial representation of the political units. This representation is often not suitable for simple integration with data collected using different underlying geographies (e.g., administratively defined regions, watersheds, swaths, or pixels). Political and administrative representations may also change over time as boundaries change, units split or merge, or data-gathering organizations change their techniques. If not appropriately taken into account, such changes can seriously affect the continuity and quality of time-series data. Because respatialization requires a spatial model, it is an instance of *model-based* integration to distinguish it from more general *semantic* integration based on an ontology. Respatialization is yet another dimension to the representation of space and place that requires research and algorithm development to define, for example, relationships between placenames and coordinates, or to address the shifting reporting zones of censuses. In the case of CIESIN's Gridded Population of the World (GPW; Tobler et al. 1997), respatialization transforms data collected for national and subnational administrative units into population totals and densities on a grid of spherical quadrilaterals, essentially a set of pixels defined by lines of latitude and longitude (Tobler et al. 1997), allowing researchers to integrate GPW with other gridded datasets (e.g., remote sensing data), to reaggregate GPW to alternative spatial units (e.g., watersheds, biomes, or metropolitan regions), and to weight other variables by population characteristics.

Integration through concepts of space and time

While the term spatial tends to dominate in the literature, the processes that modify systems are dynamic, and should more correctly be described as spatio-temporal. Moreover, the issues raised by data embedded in space are similar to those encountered in data embedded in time. In this context, spatial is used as an umbrella term to include spatio-temporal, as well as geospatial and geographic when the relevant space is the surface and near-surface of the Earth.

In recent years GPS, video, and other technologies have created a potential wealth of information about the spatial dynamics of movement by individuals, animals, vehicles, and other objects through various spaces. Developing theory and associated analytic techniques has proven more problematic, however, as it has for spatial data more generally. The problems of extracting useful information from networks of video cameras in human-built environments need to be resolved before we can understand how buildings and other structures constrain and channel human spatial behavior or before we can build models to predict the behavior of crowds and to improve urban designs.

Other aspects of spatial dynamics call for integrative space–time perspectives (Hornsby and Yuan 2008; Lin and Batty 2009), including the diffusion of ideas and innovations, and the geographical spread of peoples and cultures. In the humanities, the focus turns to relativistic as opposed to absolute spaces, and to the representation of spaces as they might have been in historical times or under the influence of cultures with different world views. Three-dimensional animations of movements through space can enhance understanding of architecture on human behavior or of archaeological structures and their human uses in ancient times. Virtual models, visualizations, and moving objects provide a rich approach to sensing changing forms and roles of landscapes through time. However, there are issues that require extended research if we are to validate the value of investments in multidimensional and dynamic visualizations and models.

Multidimensional visualizations provide spatial "eye candy," but we know far too little about the processes by which humans extract meaning and learn from such visualizations and from spatial data more generally, and about ways to improve those processes. Attention is needed to discover research-based principles for how to design multimedia material (i.e., the science of instruction) and to formulate a research-based theory of how people learn from words and pictures (i.e., the science of learning concerned with the nature of spatial thinking in complex cognitive activities such as comprehension, reasoning, and problem solving). Research is needed to determine how people learn about spaces through direct experiences, maps, and other visualizations, and about how individual and group differences impact spatial thinking and spatial abilities more generally. The work of the Spatial Intelligence and Learning Center (SILC), a multi-campus and multi-disciplinary research team from Temple University, Northwestern University, the University of Pennsylvania, the University of Chicago, and Chicago Public Schools, is especially important in documenting the learning outcomes from different ways of visualizing spatial information (see http://spatiallearning.org/). SILC is funded by the U.S. National Science Foundation as one of six Science of Learning Centers.

Moving beyond spatially intuitive thinking

Students are familiar with virtual spaces and the power of imaging through video games and digital movies. Whereas such experience may add to one's spatial skill set, it does not obviate a need for formal exposure and in-depth understanding. Yet, although one would insist that a student learn something of statistical theory before using statistical software, the same is not true of spatial software—in the spatial arena, the development of relevant theory and concepts has lagged far behind, and it is clear that a wide gap exists between the power and accessibility of tools on the one hand and the ability of researchers, students, and the general public to make effective use of them on the other. Examples abound.

To give one simple case, the NRC (2006) report on *Learning to Think Spatially* documents a 2003 article in *The Economist* (5/3/2003) in which mapping software was used to create a colorful illustration for a news story about the North Korean missile threat. Different missile ranges were depicted as concentric circles on a Mercator projection, despite that projection's severe distortions at high latitudes (on the Mercator projection the Poles are at infinity). When the map was corrected in a subsequent issue (5/17/2003), the 10,000-km missiles that according to the first map could barely reach the western Aleutians were shown to reach of the North Pole and to have Minneapolis comfortably in range. The distortions introduced by flattening curved spaces are but one of a host of spatial concepts that affect the use of these powerful technologies, and must be part of the training of researchers and educators across the full range of disciplines, something that is rarely seen in traditional approaches to curricula.

The growing body of literature on spatial concepts, in disciplines as diverse as cognitive psychology, mathematics, geography, and philosophy, identifies and enumerates basic elements of a spatial perspective. Some of these concepts, such as distance and containment, are acquired informally in early childhood, whereas others are encountered or formalized much later, or remain problematic even to graduate students. Several researchers have published lists of such concepts. Gersmehl (2005), for example, lists 13 spatial concepts as fundamental to a geographical perspective, while Newcombe and Huttenlocher (2000) list 11 spatial concepts as fundamental to their work at SILC on the development of spatial cognition. Mitchell (1999, 2005) and de Smith et al. (2009) organized their introductions to the analysis of spatial data using GIS around spatial concepts. On the other hand, the actual design of GIS user interfaces continues to be driven more by legacy and implementation than by any fundamental conceptual organization—which may explain why much GIS software has a reputation for being difficult to use.

At the Center for Spatial Studies, University of California, Santa Barbara, we have developed and published online a basic ontology of spatial concepts (http://www.teachspatial.org), linking each entry to its original sources. We have scanned the literature of many disciplines from geography and psychology to architecture in this effort, and have to date documented 186 such concepts. We have developed several organizing schemata to give structure to the collection, including hierarchical relationships (some concepts are subsets of others), semantic similarity (some concepts have different names in different disciplines), and formality (some concepts are formalizations of other intuitive concepts). As we continue to develop the site, we plan to include instructional materials focused on advanced concepts for critical spatial thinking. We use the word *critical* in the sense of reflective, skeptical, or analytic, implying that the successful application of spatial perspectives can never be rote, but must always involve the mind of the researcher in an active questioning and examination of assumptions, techniques, and data if it is to meet the rigorous standards of good scholarship.

One way to define critical spatial thinking is in relation to the use of spatial tools and data—as the mental processes that accompany the use of these technologies. Critical spatial thinking is in sharp contrast to rote button-pushing, and implies that the processes of data manipulation, analysis, data mining, and modeling provoke and *require* critical thinking, about such comparatively profound issues as scale, accuracy, uncertainty, ontology, representation, complexity, projection, and ethics. We see spatial technologies as an essential, integrating element that cuts across disciplines through common language and concepts.

The remainder of this section discusses a selection of these spatial concepts, focusing on three that are of an advanced nature, and are typically acquired during senior undergraduate or graduate education, if ever. We discuss them here as examples of the concepts that are needed to underpin the critical spatial thinking skills that we might expect of spatially aware scholars.

Anselin (1989) identified two properties as particularly important in the analysis of spatial data, but likely to cause conceptual difficulty even at the graduate level. Spatial heterogeneity refers to the tendency for phenomena distributed in many spaces, notably the space of the Earth's surface, to be statistically non-stationary. Spatial heterogeneity confounds attempts to generalize from spatial samples, because results of an analysis of a limited area will change when the boundaries of the area are shifted. Instead specially adapted methods have been developed in recent years that are place-based and local, yielding results such as model parameter values that vary spatially (Anselin 1995; Fotheringham et al. 2002). These techniques represent a radical rethinking of the traditional nomothetic demand of science that gives greatest significance to results that are true everywhere, at all times. Anselin's second concept, spatial dependence, refers to the tendency for spatial data to exhibit short-run spatial autocorrelation, a property that forms the basis of the fields of geostatistics and spatial statistics (Cressie 1993; Haining 2003). Unless it is addressed explicitly, spatial dependence can lead to artificially inflated degrees of freedom and the enhanced possibility of Type I statistical errors (rejection of the null hypothesis when it is true). These concepts are also well recognized in the analysis of time series.

Although the origins of statistical theory lie in the controlled experiments of pioneers such as R. A. Fisher, disciplines across the social and environmental sciences frequently deal with data gathered from experiments that are natural, relying on data over which the investigator has little or no control. Because these sciences frequently deal with data that are framed in space and time, they encounter the issues associated with spatial dependence and spatial heterogeneity. Yet students in these disciplines learn essentially the same introductory perspective on statistical theory as those in experimental psychology, and little attention is given to the special properties of spatial data. The concepts addressed by Anselin's two properties ensure that an analysis of social data from the census tracts of a city, or ecological data from field plots, will be unlikely to justify the traditional assumptions of random and independent sampling from some real or imagined population.

One of the most problematic spatial concepts is scale, in both of its dual meanings of extent and resolution. Dependence of results on extent, as well as the difficulties of generalization from any limited area, have already been addressed in the context of spatial heterogeneity. Resolution addresses the impossibility of a perfect representation of the infinite complexity of many spatially distributed phenomena, and the consequent necessity for generalization, approximation, sampling, or other mechanisms to remove detail. Scale issues tend to be compounded by the spatial resolution of acquisition systems, which may have little to do with the spatial resolution needed for accurate analysis and modeling, or for effective decision making (for discussions of the common issues of scale across diverse contexts see, for example, Levin 1992; Quattrochi and Goodchild 1997; Tate and Atkinson 2001; Mandelbrot 1982). In spatial analysis in the social sciences, scale and related issues are recognized in the form of the ecological fallacy (King 1997; Robinson 1950) and the *modifiable areal unit problem* (Openshaw 1983). We consider it essential that scale-related issues be part of the critical frameworks of researchers in any discipline working with spatially aggregated data.

The education challenge

We find that students are inadequately trained in the challenges of working with phenomena embedded in space and time, and that there is a need to engage them both in research on advancing the theory and technique of critical spatial thinking, and in applying critical thinking to research in a range of disciplines if they are to develop as leaders of a spatially enabled scholarship that is better prepared to use the evolving technologies, and better equipped to exploit the growing flood of spatially referenced data.

The problems of statistical inference from spatial data provide an example of the need for critical spatial thinking. Issues abound in the use of directional statistics, and in directional anisotropy in spatial covariances. Critical spatial thinkers understand the assumptions underlying spatial data and the effects of scale and non-stationarity on research outcomes. They appreciate the difficulties of inference from multidimensional data when they are subject to dimensionality reduction and the problems and implications of uncertainty in spatial data that might leave their users uncertain about the true nature of the world they represent. In addition, critical spatial thinkers can use geostatistical theory to provide a more rigorous basis for interpolation in spatiotemporal data.

Reference has already been made to a general lack of preparation in critical spatial thinking in our education system. Although spatial tasks such as block manipulation are common features of intelligence tests, it is rare to find students being prepared for them in any systematic way. One can speculate about the reasons for this. Perhaps spatial thinking is regarded as innate, an unmalleable skill possessed by some and not others (there are documented links between some spatial skills and gender, for example; Voyer et al. 1995); or perhaps spatial skills are regarded as trivial, acquired in early childhood, and in no way comparable to mathematical, logical, or verbal skills.

A recent report of the National Research Council (NRC 2006) defined spatial thinking as "a cognitive skill that can be used in everyday life, the workplace, and science to structure problems, find answers, and express solutions using the properties of space. It can be learned and taught formally to students using appropriately designed tools, technologies, and curricula." The report documented the lack of attention to spatial thinking in formal curricula, despite assertions that it is a primary form of intelligence (Eliot 1987; Gardner 1983), and called for "a national initiative to integrate spatial thinking into existing standards-based instruction across the school curriculum, such as in mathematics, history, and science classes… to create a generation of students who learn to think spatially in an informed way." The report viewed spatial thinking as "an amalgam of three elements: concepts of space, tools of representation, and processes of reasoning" (p. 12). Although focused on K-12 education, the report includes a series of rich and compelling examples of the application of spatial perspectives whose applicability extends across disciplines and all levels of education. A recent article in *Science* (Holden 2009) quotes David Lubinski of Vanderbilt University from a presentation to a National Science Board workshop on innovation: "(D)espite their importance in science, particularly in fields such as engineering, robotics, or astronomy, spatial abilities are getting short shrift both in school curricula and in programs trying to spot precocious youths."

Dating back to the work of Smith (1964), findings continue to show that individuals who are more spatially adept have greater success in higher-level problem solving (Kozhevnikov et al. 1999, 2002, 2005). SILC has assembled evidence that spatial intelligence can be enhanced, and that heightened spatial abilities among adolescents can be a predictor of future science career paths (Shea et al. 2001). Legé (1999) has argued that lack of spatial awareness and skills hinders students' ability to perform many tasks that are essential in the science and engineering disciplines, while Wheatley (1997) argues that advancing teachers' knowledge of the efficacy of such spatial skills as visualization can help students to become better solvers of math problems.

We live in a global academic world that is dominated by the need to solve complex problems that are embedded in space and time, and to bring spatial perspectives to scholarship. This twenty-first century world is collaborative, enabled by cyber infrastructure, and is highly interdisciplinary. It is evident that students should be trained to the standards of a critical spatial thinker, including:

- the potential to contribute critical spatial understanding to research at the interface between disciplines;
- the ability to work in a team;
- the ability to explain the space–time context of research to non-experts;
- the ability to develop new and highly original spatially informed research ideas;
- the experience to enable sustained and successful research dialog within an international community of spatially aware scientists;
- the ability to disseminate spatial understanding of research through teaching and curriculum development at K-12 and undergraduate levels; and
- the ability to transfer spatial technologies and spatial concepts for research across different knowledge domains and problem sets.

Achieving these goals will require a combination of conventional course-based curriculum, intensive peer-to-peer interaction, project-based learning, and engagement with activities across the educational spectrum (in the community and region, on campuses, nationally, and internationally).

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