

# UC Santa Barbara

## Specialist Meeting Position Papers and Reports

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Spatial Thinking across the College Curriculum, Position Papers

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## Position Papers, 2012 Specialist Meeting— Spatial Thinking across the College Curriculum

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## Advancing STEM Education, GIS and Spatial Thinking

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The call for this specialist meeting asserts that spatial abilities are related to both *success and participation in STEM*. More generally, it implies that spatiality is the unifier of [most] academic disciplines. These assertions beg many questions, perhaps beginning with, *what* is our goal? What should the educational community and industry partners do to clarify the need for and advance spatial abilities across the collegiate and K-12 curricula *in the near term*, from research and practice to curriculum development and promotion?

Uttal and Cohen's (2012) meta-analysis lends clarity to the many critical dependencies STEM education holds for spatial abilities and training. The longitudinal work of Wai, Lubinski, & Camilla (2009) demonstrate the propensity of most STEM learners to score well on measures of spatial skills. *Learning to Think Spatially* (NRC, 2006) articulated the value of Geographic Information Systems (GIS) in serving a need to develop spatial skills in learners. It's my contention that at multiple levels and use cases, GIS could be of great value in providing spatial skill development through well defined STEM curriculum and instructional practices. GIS could also be of substantial benefit in *assessing* spatial skills development. While learning to use GIS provides learners with 21<sup>st</sup> century career skills, STEM teachers also use GIS in inquiry-oriented instruction to teach content, using real-world problems. To advance the development of spatial skills throughout K-12 STEM, collegiate STEM, and beyond (e.g., <http://esriurl.com/spatialuniversity>), Esri Education works in at least three interwoven spaces: educational research, open educational resource development, and educational marketing.

At Esri Education, we commit time and energies to supporting STEM and spatial thinking, especially in K-12 and informal education. High quality STEM learning supports national priorities in STEM-based career development and collectively, a workforce that is more globally competitive. STEM learning requires effective curriculum standards, high-quality teacher preparation, and supporting national policies and frameworks (NSB, 1997). The significance for targeting K12 (including university teacher education programs) cannot be overstated. "Nearly four in five STEM college students said they decided to study STEM in high school or earlier (78 percent). One in five (21 percent) decided in middle school or earlier" (Harris Interactive, 2011).

Supporting and contributing to GIS educational research efforts are capstones in my work to advance spatial skills, student outcomes, and teacher professional development across all disciplines, including STEM. Over the last six years, we have hosted researcher meetings at academic and industry conferences. The coming year holds plans for continuing that effort with intentions to support the development of a formal *GIS education research agenda* in collaboration with multiple partners from academia and industry. Such an agenda has been called for by scholars, the GIS Education Working Group (<http://edgis.org/research>), and the Esri

academic advisory board. This agenda will undoubtedly include substantial recommendations that foster research on GIS as a tool for acquiring and assessing spatial abilities.

Open Educational Resources (OER) represent the intersection of spatial skills, STEM content, and GIS technology for the education team. Adopting a Creative Commons license (Attribution-Noncommercial-ShareAlike), Esri Education sponsors hundreds of activities in ArcLessons, the EdCommunity blog, and various video outlets. Our OER efforts include instructional resources, software, and data - all designed to foster spatial thinking. Resources are formed as single or multi-day lessons, modularized “plug-in” activities, units, and even whole courses. These instructional materials target both traditional content acquisition and skill building, including problem-solving, critical thinking, and spatial thinking. Summarily, our OER efforts are an attempt to democratize both spatial skill and GIS skill development across nearly all instructional boundaries.

Esri Education is driven by geographers and educators who are tasked with bringing spatial thinking and analysis by way of technology to the entire education space. With the aid of the Esri academic advisory board, we continually monitor and adjust our efforts to best align with community need. As a result, the team engages in a very wide range of activities, including designing promotional materials, creating a presence at key educational conferences, and developing literature and technology products that serve education. Each of these outlets includes and often frequently targets, spatial thinking and skill development in the context of GIS.

Within our ongoing efforts, lies the capacity to support the development of educational resources, research, and promotional work that extend spatial thinking across the K12 and collegiate curricula. What messages, materials, and technical developments should industry contribute to the promotion of spatial abilities across curricula? When is the appropriate time and what form should such efforts take?

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## Inventing and Learning from Novel Diagrammatic Procedures

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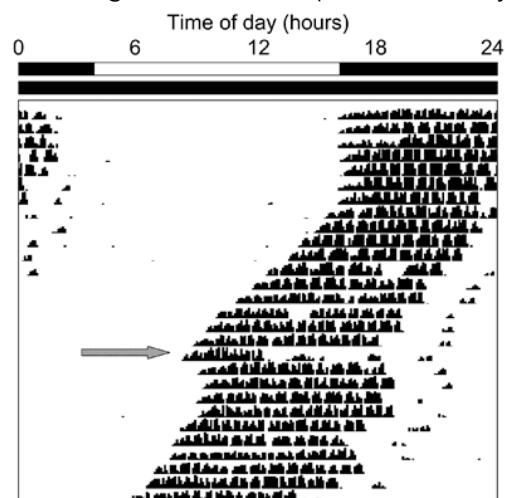
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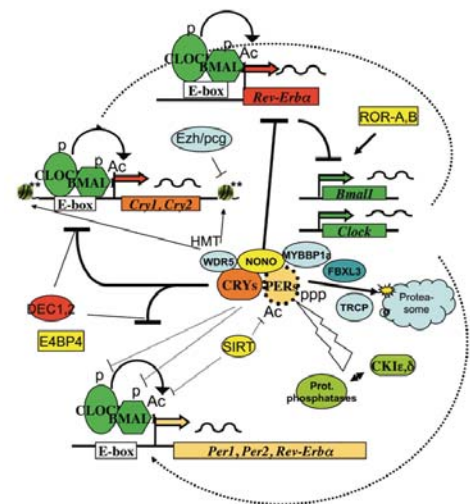
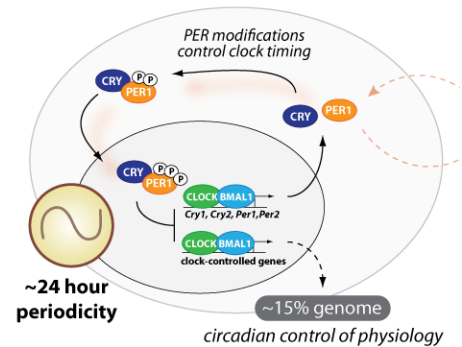
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Diagrams play a central role in scientific reasoning and are distinctive in their use of space to position and relate representations. Diagrams serve not only to convey strategies and protocols of inquiry, data, and explanations, but also to reason about them. Modifying existing diagrams can suggest new strategies and explanations, and modifying data representations in particular can provide new insights into a phenomenon. Since many diagrammatic formats (e.g., bar graphs) and modes of reasoning are used widely across disciplines, once mastered, they can be understood and applied in new domains. But just as there is distinctive content in each discipline, often there is a need to develop and use distinctive diagrammatic tools as well—posing challenges to scientists and students alike.

Our research team has focused on circadian rhythm research and the new diagrammatic techniques developed in this field. I briefly sketch three examples of new representational formats that circadian researcher have created or applied, and which new practitioners must master and learn to employ in their own thinking. The first of these traces how periods of activity change over days. A line graph plotting activity against time will show oscillations as waves, but does not convey subtleties of the daily pattern. For this the actogram was developed in the early 20th century. Although it took circadian researchers several iterations to arrive at the diagrammatic format now widely employed, it is one that is quite easy to learn to interpret. As shown in the actogram on the right, a new row is used for each day and when activity occurs (e.g., a mouse runs on a wheel) a vertical mark is placed in that row. A variety of techniques have been developed for indicating the experimental conditions employed (e.g., regular periods of light vs. dark each day). The diagram at the right shows the behavior of a mouse when it was first exposed to light from 4:00 to 16:00 each day and then, on day 7, shifted to constant darkness. It can be seen that after this shift the mouse initiated activity earlier each day, indicating that its endogenous clock has a period somewhat less than 24 hours. On day 18 (grey arrow) a light pulse perturbed the rhythm 4 hours after activity began, and the effect on the activity of the mouse on subsequent days is apparent.

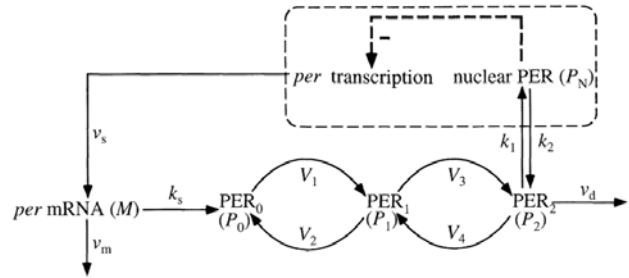


A second example involves the representation of the mechanism proposed to explain circadian rhythms. Since the 1960s it has been accepted that when external cues such as light are removed, organisms continue to exhibit rhythmic behavior (albeit differing slightly from a 24-hour cycle). This indicated that the mechanism existed inside organisms, but it was only with the rise of molecular biology that researchers were able to show that this endogenous mechanism was a molecular clock within individual cells. They identified certain genes and the proteins they expressed as key components, and learned how they were organized into interacting cycles capable of sustained oscillation. Crucially, the cyclic organization of the mechanism involves both positive and negative feedback loops. These loops can be described linguistically, sometimes in a single long sentence, but they are best understood when represented spatially in diagrams. The top figure on the right exhibits the basic idea of a negative feedback loop in which two proteins, Per (yellow oval) and Cry (blue oval) are synthesized in protoplasm, reenter the nucleus, and inhibit (line with straight end) their own further transcription. Here space is used both to represent actual structures (e.g., an inner ring represents the boundary between the cell's nucleus and cytoplasm) and more abstractly to indicate processes involving different entities. Once one learns to interpret such diagrams, that skill can be extended to more complex versions, such as the diagram to the right that incorporates additional components discovered over the past 15 years and the multiple feedback loops in which they figure. Part of becoming a researcher in the field involves mastering how to use this mode of representation as a tool for considering where new components might fit and different ways their operations might be organized.



The behavior of simple mechanisms often can be understood by mentally rehearsing their successive operations. This is grossly inadequate, however, as a strategy for predicting and understanding the behavior of mechanisms with feedback loops. For this, computational models are needed. To construct such models it is necessary to identify properties of the parts and operations of the hypothesized mechanism that can usefully be quantified and hence used as variables in mathematical equations that capture the mechanism's activity. Decisions must then be made about which of these variables to include, which parameters might need to be added, and the number and form of the equations in a particular model. The diagram below includes labels for some of the parts and arrows for some of the operations in the diagram at the top of the page. For example,  $M$  is the concentration of *per* mRNA,  $P_2$  is the concentration of the phosphorylated PER protein, and

there are arrows for such operations as translation of *per* mRNA into PER, PER transport, PER transcription, inhibition, and decay. The relevant property of each operation is its rate, but each rate is a calculated variable that depends in part on a maximum rate parameter (subscripted  $v$ ,  $k$ , or  $V$ ). Frequently different modelers develop somewhat different models, and diagrams such as these are extremely important in tracking and understanding these differences.



Each of the representational formats briefly introduced play central roles in circadian rhythm research. Each of them has a history as they have been modified over time. Each requires learning before novices can use them effectively to represent information and reason about it. But once sufficiently mastery is acquired, they provide potent vehicles for reasoning in the discipline. An important element in becoming a participant in this and similar research fields is to learn to understand and be able to reason with the distinctive diagrammatic formats of the field; accordingly, a critical task for educators is to learn how to cultivate these skills across the variety of distinct scientific disciplines.

## Spatial Thinking: Learning Outcomes and Spatial Meta-Concepts

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I have had the distinct pleasure of exploring and considering spatial thinking from both bottom up and the top down perspectives. The former has come in the form of my primary research interests in spatial cognition, spatial knowledge acquisition, navigation, and scale. The latter, has been a direct result of my role as leader of the twice yearly GIS Institute at Harvard and similar teaching experiences with university level students and above. The Institute has exposed me to the process that emerging scholars must pass through to effectively integrate a spatial perspective into their research. The challenges of each of these are unique with some interesting overlap that might offer an avenue to explore the primitives of space and building blocks of spatial thinking.

Learning outcomes and program goals are an effective mechanism in the development of curricula and teaching practices. As I will advocate later, integrating space into college, program, and course level learning outcomes is an important first step, but should not be the final goal. Identifying a common lattice, or set of lattices, from which spatial knowledge and spatial thinking can be developed is the logical extension that can ensure its deep curricular integration. The first step in this process is a better understanding of meta-spatial concepts that might serve as the lattice. Once such concept with which I am most familiar is scale, both as it defines the spatial extent of study and how changing scale can affect the nature of other spatial concepts.

As an educator I have worked with elementary school students, undergraduates, graduates, and faculty in the broad area of geographic knowledge and spatial thinking. I have developed undergraduate courses that are intended to knit together the central themes of geography (more than space and place, but I find those a good starting point) with a spatial perspective that employs GIS as the lens through which knowledge can be created. The experience of seeing undergraduate students from diverse backgrounds struggle with and eventually succeed in applying spatial concepts in an analytic research environment had a direct and positive influence on my later development of similar training for the already seasoned researcher.

The challenge of working with researchers with a well developed sense of their disciplinary epistemology poses both challenges and opportunities for scholars in fields with a sense of the spatial dimension (not just geographers). Other disciplines' unique ways of creating knowledge forces those scholars to consider new ways of knowing (like taking a spatial perspective, spatial thinking, spatial analysis, and spatial communication) within the context of a well defined landscape. Finding common language is one of the first hurdles; fortunately one of the advantages of spatial language is that the naïve or lay definitions for certain terms is often not



that far from the formal definition of the term (cluster, dispersion, random, etc.). Bridging scholars from the naïve to the formal is a process that often has satisfying results. However, one of my biggest challenges in shepherding scholars on the spatial path is ensuring their spatial turn doesn't dominate and that as the spatial "expert" I don't dominate either.

In a shared search for knowledge it is often the leader, or teacher, who takes the dominant role; taking a step back and allowing the student to lead is an important step toward allowing space and spatial thinking to augment the process of knowledge development, not control it. Furthermore, this role reversal often leads to discoveries about spatial thinking and the nature of space and spatial analysis that are only revealed in context sensitive settings, some of which might have been previously unexplored from spatial perspective. In my own teaching I often use the concepts of "units of analysis" and "area of study" to help researchers develop an understanding of the spatial dimensions of their work. This is a useful bridge for researchers from a wide range of fields, despite the quantitative or statistical sound of the terms. Researchers from the humanities, social sciences, sciences, and engineering, understand the importance of scoping the work they are doing and clarifying how they will do their work. From a spatial perspective it gives them some solid ground from which to begin exploring the power of space.

Scale is also an effective tool for spatial thinking. Naïve learners, children, and seasoned researchers can all come to understand the importance of space through scale. Cognitive scientists have documented the role that spatial extent plays in the solution of common problems. Spatial search conducted on a desktop is quite distinct from spatial search conducted in a city. That the difference in those real world settings is manifested in how the problem is conceived, planned, and solved cognitively is a testament to the importance of scale and space to how we think spatially. Scale can change the way we use frames of reference, landmarks, and the cognitive mechanisms we employ when making spatial decisions (facing spatial problems).

Here scale is a useful tool to consider how we might link the seasoned researcher or college student with the child or naïve problem solver. The researcher might focus on the spatial extent of their study site and implications this choice has on data selection or relevant units of analysis. On the other hand using a variety of scales (spatial extents) to explore mapping or spatial arrangements in an elementary classroom can expose students to the role that space and scale have on how we think about the world around us. Exposing students to a broad range of spatial concepts and primitives is a laudable goal; enhancing this knowledge by reinforcing how the response to changing scale is equally important, more so if one of our goals is the development of flexibility in thinking and problem solving. Some concepts might be more or less sensitive to scale. A frame of reference essential in small spaces, like an egocentric frame, might be inappropriate at a different scale. The flexibility with which a person can adapt to changes in scale is one way to approach teaching and learning or to identify strengths and weaknesses in spatial thinking.

Considering scale, or other meta-spatial concepts, as structures from which we can organize and deliver training in spatial thinking and problem solving would be an interesting sub-goal of the workshop. It is important that we don't assume we know how such meta-concepts affect other spatial concepts or learning goals. Identifying learning outcomes is a simple first step, but achieving such outcomes while reinforcing spatial knowledge should be a central goal of a community interested in the integration of spatial thinking across the college curricula. The importance of space to the community of scholars meeting in Santa Barbara in December is not in doubt. However the development of an effective strategy for deploying spatial thinking across the curriculum takes more than agreement; developing strategies that effectively emphasize the power of space for all disciplines is of paramount importance.

## Developing a Spatial Minor at the University of Redlands

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**M**y interest in spatial thinking grew naturally out of my discipline, archaeology, which is inherently spatial—concerned with the distribution of artifacts on the landscape. In 2007 I participated in the Spatial Analysis in the Social Science Curriculum Workshop at UC Santa Barbara, where I first explicitly grappled with the challenges of delivering spatial content—and especially spatial technologies like GIS—in an undergraduate curriculum. Then, my primary concern was whether the class I was trying to develop should use spatial technologies to help teach my discipline, or whether my discipline was a useful platform for teaching students how to learn spatial technologies. Ultimately I developed a lab based class called “Mapping People, Mapping Place” which attempts to achieve both goals, though I think that the tension between teaching spatial tools/concepts and teaching disciplinary content is still at the heart of a college spatial curriculum.

The spatial proximity and formal relationships of the University of Redlands with ESRI, headquartered in Redlands, make spatial thinking an obvious area of emphasis for us. Only recently, however, have we attempted to formalize a spatial thinking curriculum. Since the spring of 2012 I have led an *ad hoc* group of faculty working to develop an interdisciplinary spatial thinking minor, which will be submitted to the College of Arts and Sciences curriculum committee this fall.

Our effort to develop a spatial minor is affected by a number of opportunities and challenges, some of which are unique to the University of Redlands and some of which are common across many undergraduate institutions. Common challenges include: a small and relatively fixed number of faculty with pre-existing spatial expertise; considerable disciplinary diversity in use of spatial approaches; and a lack of a clear central department or program, like Geography, to house, advertise, or coordinate a spatial curriculum. Unique advantages include a rare “spatial administrator,” our Director of Spatial Curriculum and Research (Diana Sinton) who has coordinated the efforts of faculty and administrators; and a grant from the Keck Foundation, which we used to establish a Spatial Fellowship program for Redlands faculty to help faculty develop spatially-themed courses and research projects.

In the course of constructing the minor we have encountered a number of issues that are surely common to many undergraduate educational contexts, including:

- How closely should the teaching of spatial thinking be tied to spatial technologies, especially GIS?
  - Given that our explicit goal is to make our spatial curriculum as inclusive as possible, our working group fairly quickly concluded that we did not want to link spatial thinking exclusively with technological applications like GIS. Other free, user friendly interfaces like Google Earth provide useful platforms that provide fewer barriers to entry to new

students. We did, however, agree that a student graduating with a spatial minor should demonstrate “graphicacy”—the ability to interpret and communicate spatial concepts, which does imply some competency with software used to produce maps and other spatial representations.

- To what extent should the minor include courses from disciplines like English or History, which may teach courses that are grounded in “place” but may only weakly explore actual spatial relationships?
  - Courses such as “African Diasporic Literature” or “The History of Europe” cannot help but deal with geography at some level, but most do so only implicitly with respect to core spatial thinking concepts. In the construction of our minor we have adopted a “missionary” approach in which we combed the course catalog for potential spatial courses and then approached the faculty who teach them to discuss the course and our hopes for the spatial minor in more detail. Those who expressed an interest in revising their course content to align with the spatial minor were referred to our Spatial Fellowship program and support staff on campus who can assist with spatial course development. This is an intentionally long-term strategy designed to recruit and train faculty to contribute spatial courses, even if the central thrust of their research is not spatial.
- To what extent should the minor include courses from disciplines whose content is inherently spatial, like geometry or physics, but that do not explicitly use the language or concepts of spatial thinking and do not explicitly link their content to an understanding of constructed “places”?
  - Our working group struggled with this issue and found that it greatly tested our common understanding of spatial thinking. Why, the physicist in our working group wondered, shouldn’t a math course on topology be counted as spatial even if no readings from Yi-Fu Tuan are assigned?
- Are spatial concepts best taught through a sequence within a discipline, culminating in a meaningful case study, or by exposing students to the breadth of spatial approaches across disciplines?
  - Our working group felt strongly that a primary benefit of spatial approaches is to reveal the interdisciplinary, multi-scalar, interconnected nature of virtually any topic. But we also confronted the limited contact time for students completing a minor, especially one spread across multiple departments.

Our near-final model for a Spatial Thinking Minor includes the following elements:

24 units of study including the following requirements:

**I. Two Core courses**, ideally to be completed before the end of the sophomore year but can be taken at any point:

- SPA 100 Foundations of Spatial Thinking (a course reviewing core concepts of space and place, scale, distance and direction, etc., along with core tools of representation like maps and graphs)
- SPA 110 Introduction to Spatial Analysis and GIS

**II. Four Elective Courses**, taken from *at least two* of the following categories:

- Methods and Representations (including courses from Art and Math)

- Culture and Communities (including courses from English, Government, History, Religious Studies, and Anthropology)
- Physical World (including courses from Biology, Chemistry, Environmental Science, and Physics)

## Humanities and Spatial Literacy/Spatial Thinking

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Over the past two decades, the humanities and social sciences have advanced a more complex and nuanced understanding of space. Today, humanists are acutely aware of the social and political construction of space and its particular expression as place. This understanding no longer seems new because humanists have embraced it eagerly; now, we all recognize the particularity of space, the importance of place. It is, in fact, a postmodern view. But for all the uses we make of this insight the concepts of space and place employed by humanists frequently are metaphorical, not geographical. Far less often have we grappled with how the physical world has shaped us or how in turn we have shaped perceptions of our material environment.

There has also been a shift towards using spatial technologies in a wide range of humanities disciplines that is increasingly referred to as spatial humanities. Above all, GIS demands the use of spatial questions in its applications, whereas most humanists think rarely about geographical space. The fact that humanists typically do not employ geographical concepts in their analyses, however, begs several questions: Do humanists discern a connection between their methods and the methods of geography? Do they understand how spatial competencies can affect their scholarship? Do humanists perceive themselves to be spatially literate?

In 2009, Ian Gregory (geography, Lancaster University) and I received a SPLINT (Spatial Literacy in Teaching) grant from the UK to investigate spatial literacy in the humanities. The project, "GIS and the Humanities: Towards an Educational Strategy in Britain and America," aimed to map core spatial competencies onto the themes and methods embraced by historians and other humanists in their work, based on consultation with user communities. The community of interest included the disciplines of history, linguistics and literary studies, cultural studies, religious studies, and archaeology, among others.

One part of the project involved an online survey of over 200 humanists from the UK and US. We asked about the use of spatial technologies, the need for spatial skills, and institutional barriers. Our aim was to make recommendations about how to improve the usefulness of spatial methods and tools in higher education at both the undergraduate and graduate level. The results, although not surprising, confirmed what we had learned from user groups. Overwhelmingly, respondents believed spatial skills needed to be improved across the board, with spatial thinking being seen as particularly important and spatial analytic skills as notably lacking among current students. (Significantly, they also acknowledged a need to improve their own literacy and skills as well.) The number of respondents who cited the importance of these skills increased somewhat when asked about the graduate level but the order remained the

same. Respondents shied from a tools/methods-oriented approach when asked about undergraduate and graduate curricula, overwhelmingly citing the need for instruction in spatial thinking (94 percent), cartographic representation, and spatial analysis. They cited the need for exposure to critical theory, especially at the graduate level. Training in GIS and other spatial software was clearly a secondary concern, and even here the emphasis was not on mastery of the tool as much as on understanding spatial data and its development. All the various means for providing skills—coursework, workshops, online instruction, and labs, among others—received endorsement from three-quarters of the respondents, with nine of ten agreeing strongly that the best method of learning was through project work, including at the undergraduate level.

How can the humanities cultivate spatial literacy, which is the first step toward making the humanities truly spatial? Scholars at undergraduate, postgraduate and professional level must become aware of the importance of geographic space and how it affects them and their discipline. It also is important to help scholars understand the different ways in which space can be conceptualized, as well as recognize how space linked with time helps us achieve a more complete understanding of human activity. In this matter, the history of geographical thought is valuable, especially the development of a critical GIScience literature over the past three decades.

Given the relative newness of these technologies and approaches within the humanities we recommended: **(1)** that scholars be exposed to the rapidly growing research base that employs spatial approaches to create new knowledge; **(2)** that access to the limited and disparate resources relevant to spatial literacy become more accessible to humanists; **(3)** that spatial literacy be taught formally at postgraduate level in suitable humanities courses; and **(4)** that spatial literacy be introduced at undergraduate level, especially through projects that illustrate its importance without demanding technical mastery first. Undergraduate courses should focus more on core concepts of spatial literacy and their importance rather than on technical skills. In other words, undergraduate education in the humanities first must demonstrate why space is important within their discipline. Numerous resources exist for the development of this understanding, including but not limited to materials offered by the Spatial Literacy in Teaching program,<sup>i</sup> as well the recent book by David Unwin, et al, which includes much of the work accomplished under the SPLINT grant.<sup>ii</sup>

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<sup>i</sup> See <http://www.spatial-literacy.org/>

<sup>ii</sup> David J. Unwin, Kenneth E. Foote, Nicholas J. Tate, David DiBase, eds, *Teaching Geographic Information Science and Technology in Higher Education* (Oxford: Wiley-Blackwell, 2012).

## Spatial Thinking and Spatial Technologies in History and the Humanities

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Spatial thinking across the disciplines may mean that spatial thinking is a well-defined thing that can be brought to bear on different disciplines, a hammer that can pound any nail. But what then is this mental procedure? Or perhaps it is not really a definite method at all but an attitude, an interest in how space and place might figure in one's own disciplinary territory? In the broad range of the humanities there is evidence for both possibilities. Somewhat counter intuitively an example of the latter is the use of "place" in science studies to historicize early modern science, and an example of the former is a data-driven analysis of the rise of the novel in comparative literature. History, like geography itself, can accommodate both humanistic and data-driven approaches. My interests have been oriented toward approaches that will allow us to use location, distance, and scale in the analysis of in large quantities of data so that we can see change taking place across the landscape through time

An interest in integrating space and time, as a kind of marriage of history and geography, led an interest in technologies for collecting, analyzing, and visualizing large amounts of historical data with spatial attributes; to GIS, in short. It is often held that GIS technology is merely technology, that, while it may be a sophisticated hammer, its purpose is still to pound nails. Against this I would side with the view that great advances in knowledge take place not only through shifts in conceptual paradigms and increasing specialization, but also through the spread of tools that allow us to see more than we could before. Like the microscope and telescope, GIS is a tool, but one that is particularly appropriate to a digital world and changes how we think about the world by allowing us to see more than we could before.

In the six years of its existence Harvard's Center for Geographic Analysis has been bringing the technologies of geospatial analysis into disciplines where they had little purchase in the past and teaching a generation of graduate students how to use GIS in their research. The steadily increasing demand for instruction and support is evidence that value is being added. In terms of history and the humanities it is already clear that geospatial technologies are making new large-scale research agendas practicable in an area where empirical scholarship has traditionally been individual work from start to finish, and thus necessarily limited in scope. New and sometime unexpected questions are coming to light and researchers are finding new ways to share their work and collaborate, ways that were not possible before. Scholarship in history and the humanities is become more collaborative and more cumulative as the basic datasets with which researchers work are find a long-term home on web-based platforms.



From the perspective of history, however, there are several cyber infrastructural obstacles to facilitating the use of spatial thinking and technologies. The first is the lack of a world world-historical gazetteer. GIS is about geographic space, but in the historical record “place” matters more than “space.” A person is of a place, a religious site is located at a place, tax is reported by place, a postal station is a place in itself. Places are nodes in networks (for premodern times it is easier to find the nodes than the routes between them and reliable sources for administrative boundaries before 1800 are few). A historical gazetteer, at its simplest a listing of place names with their locations in space and time, is the bridge between history’s places and spatial analysis. The major online world gazetteers are invaluable but share a common flaw: they ignore time. This is true of the Geographic Names Information System; the National Geospatial Intelligence Agency’s GONet Names Server, and GeoNames, the largest nongovernmental gazetteer (see sidebar). These systems provide between two million and ten million place names, but do not track name changes over time. This has consequences. The lack of a record about when a name is changed or a jurisdictional line redrawn eventually will result in the loss of knowledge about when the attributes of that place (population, area, etc.) are valid. Information management systems that overwrite earlier data sacrifice a longitudinal record to clerical efficiency. A systematic approach to extracting vector data from historical maps could populate a world-historical gazetteer but requires either the extension of optical character recognition technology or successful crowd sourcing of the manual extraction of data from scanned maps are beginning.

For the time being georeferenced maps scans will remain the most important source for historical information about space and place. Consistent and cumulative access to maps scans requires more than the Rumsey Map Collection’s 29,000 online scanned (some 22,000 have rough georeferencing). Old Maps Online, a UK-based project, is creating a solution: a federated system for registering, georeferencing and sharing historical map scans.

Just as important is a federated system for learning about spatial datasets. OpenGeoportal.org, led by Tufts, Harvard, and MIT with many partner institutions, is a portal which with the potential to provide a single entry for searching and previewing collections of data. A concomitant to this is a system for archiving and searching historical datasets that could be joined to spatial objects in a GIS, such as the planned World-Historical Dataverse of the Center for Historical Information and Analysis at the University of Pittsburg.

The final piece of cyber infrastructure needed for a wider use of GIS is an online platform for sharing spatialized data (as both online visualizations and downloadable data files). The goal is to make the maps and data layers researchers create accessible to others, so that others can take advantage of the accumulation of spatialized data in their own work, but also to make it possible to think spatially by composing maps through combining data layers online.

There has been significant progress in the online realm. ESRI’s ArcGIS Online and ArcGIS Explorer Online allow users to create, store and share maps and datasets, manage geospatial content, and control access to volunteered content. Geocommons, developed by the GeolIQ company is similar. In collaboration with the open-source web-mapping developer community, the Center for Geographic Analysis at Harvard is developing the WorldMap platform, allowing

users to explore, visualize, edit and publish geographically referenced information. WorldMap has an expanding list of functionalities it wishes to add, but it already allows researchers to upload large datasets and combine them with those shared by others, create and edit maps and link map features to rich media content, grant edit permission to small or large groups, export data to standard formats, georeference paper maps scans online, and share data with just a few collaborators or with the entire world. The promise of WorldMap is that it is cumulative; nearly five-thousand registered users are already uploading and sharing their data and maps, and 180,000 others are viewing their work. Working with MapStory, it will soon add animations, allowing vivid displays of change over time.

Historical georeferenced data is part of the world of big data that the digital environment has made part of our lives. As the cyber infrastructural impediments give way, GIS technology, federated geodata systems, and online mapping are likely to become part of the toolbox for the next generation of historians.

## Spatial Thinking and Reasoning Across the College Curriculum

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As a spatial cognition researcher, I have long believed that spatial thinking is at the core of a large and diverse set of disciplines, and that mechanisms of spatial thinking like reference frames may serve as a valuable connecting entity that enable us to address important research questions in an inter-disciplinary manner. Reference frames are representations that are imposed on space, thereby providing structure by assigning orientation, direction, scale and distance to the space, and offering a means for locating people and things within the space. These parameters may be set by different sources of information, including people interacting in the space, environmental features within the space, or objects contained within the space. Moreover, multiple reference frames may be imposed simultaneously that configure different parts of the space, or that configure the space at different levels of granularity. This flexibility may be beneficial for the cognitive system because it enables representations that can be set up with respect to particular tasks and goals. It also therefore requires a set of skills that can operate on these varied representations, including the ability to translate between the different types of reference frames that are derived from different sources; the ability to coordinate reference frames at different levels or scales of space; the ability to effectively communicate locations of people and things within the space with respect to different frames of reference; and the ability to navigate within the space with respect to different reference frames. The importance of these processes and accordingly the skills required to master these processes should not be understated, because reference frames as mechanisms of spatial thinking appear within a wide set of disciplines, including engineering, linguistics, perception, anthropology, education, psychology, medicine, and architecture. This ubiquity suggests that reference frames are a central mechanism for thinking about space, and further that spatial thinking may be facilitated through training in the processes that operate on reference frames, with positive consequences that cut across these varied disciplines.

In my lab, reference frames serve as a central common element for ongoing collaborative inter-disciplinary projects. For example, in a project with Dr. Panos Antsaklis at Notre Dame (Aerospace/Mechanical Engineering), we are examining how spatial thinking and the allocation of spatial attention to the environment may change as a function of off-loading key cognitive functions from the human driver to the automatic control systems of the car. We are particularly interested in the phenomenon in which drivers steer toward a stopped vehicle on the side of a road when their attention is diverted to that location. One possible explanation is that the driver is trying to align their heading which may be encoded egocentrically with the location of the roadside object which may be encoded allocentrically. We are interested in solutions to this

phenomenon that may involve the car monitoring the heading and when a drift is detected, invoking an alert system or making automatic steering adjustment.

As another example, in a project with Dr. Marge Skubic at Missouri (computer science/engineering) we are designing an interface to facilitate the linguistic interaction between humans and robots in an eldercare setting in which a robot serves as an assistive device for the elderly. The focus is on the production and comprehension of spatial descriptions, and translating between the reference frames that are selected by the human to represent and communicate spatial locations, and the reference frames that are used by the robot to store location information about the environment and to navigate.

Other projects in the lab that involve reference frames include developing a diagnostic tool to identify whether patients suffering from apraxia (an inability to reach to a target) have deficits in the encoding of space according to egocentric or allocentric reference frames, and identifying how people judge how “roomy” a car feels, which requires a coordination between the representation of the space around the body with a representation of the interior space of a car. Finally, I have worked extensively with Tim Shipley at Temple/SILC and Christoph Hoelscher at University of Freiburg/SFB and Ruth Conroy Dalton at Northumbria on projects that include an examination of the reference frames that are used during navigation in new buildings, and a determination of how they are coordinated with the organization of the building and the strategies that participants employ.

A focus on reference frames as a key spatial skill was also readily apparent at CogSci2011 which was entitled “The expanding space of cognitive science,” and for which Tim, Christoph and I served as program chairs. One of our symposia explored spatial thinking across a variety of fields including architecture, medical visualization training, cartography, geography and geosciences.

Given my research background in spatial thinking with a focus on reference frames, my history of inter-disciplinary research, and my interest in promoting the examination of spatial thinking across a variety of disciplines, I have a keen interest in this workshop, and would welcome the opportunity to share my ideas and skills at facilitating cross-discipline discussion and collaboration. I could envision reference frames serving as an organizational tool across a curriculum, and would be interested in more formally discussing the underlying spatial skills and devising a means for including training in these skills across a range of disciplines. I have been formally trained and certified to teach K-8, and taught 4th grade for 2 years before graduate school; therefore, I have some practical experience at implementing curricula. I have also been teaching at the university level since 1994.

## What are learning outcomes for spatial thinking curricula: What form should assessment take?

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The purpose of this position paper is to focus on the question of what form assessments should take when evaluating the relation between spatial thinking and STEM curricula. The first recommendation is that we need to consider effective ways of conducting evaluations of spatial interventions that do not depend solely on the random assignment of students to experimental and control conditions. I will discuss an alternative research and statistical design, the Regression Discontinuity approach. Secondly, research has now established that spatial abilities are related to success in STEM disciplines. However, we need a much more refined analysis of: (1) which specific types of content within each STEM field are impacted by spatial skills, (2) the specific mechanisms underlying these associations, and (3) a better understanding of individual differences in the spatial strategies (successful or unsuccessful) that students use when trying to solve spatially related STEM content.

### **An Alternative Approach to Design of Spatial Interventions at the College Level:**

#### **The Regression Discontinuity Approach**

The organizers of this conference make a very important point, when they state that, "...spatial thinking is not fostered in our educational system and that current practice depends more on selection of the most able students for spatially demanding disciplines than on fostering the spatial intelligence of all students." In order to determine the effectiveness of a particular spatial intervention on college student learning, it is clearly critical to use appropriate research design methods. However, for a wide variety of reasons, not all researchers and curriculum developers can apply the gold standard of research design by randomly assigning college students to experimental and control groups.

In a recent paper that I co-authored with Sheryl Sorby and others (Sorby, Casey, Veurink, & Dulaney, 2012; under review, *Learning and Individual Differences*), we used a different research design to determine the effectiveness of spatial interventions on Michigan Tech engineering students at risk of poor spatial skills. The major contribution of this new methodology was to confirm and validate 15 years of prior findings on spatial skill interventions conducted at the same Engineering Program—by applying a more statistically sophisticated approach—Regression Discontinuity (RD). A problem interpreting the past results is that there might have been a selection bias, since students who failed the initial spatial test could decide to either take the intervention or serve as the comparison group. Thus, the students choosing to take the intervention may have had higher motivation levels than the students not taking it.

Our new study was designed to examine the benefits of an intervention targeted to the freshmen engineering students who failed an initial spatial assessment during orientation at Michigan Tech. It was not possible to randomly assign students to conditions. Instead, we *required* all students who failed the mental rotation test during orientation to enroll in the spatial intervention course. This enabled us to address the question of whether the spatial intervention was successful in raising students' spatial skills through an alternative non-experimental design. Using a RD pre/post-test analysis, we found a treatment effect by demonstrating a discontinuity or jump in the regression intercepts at the cutoff score of the pretest variable, with the intervention group performing at higher levels than would be expected if there had been no intervention. Using the same RD analysis, the intervention also showed transfer effects, improving calculus performance of the students in the intervention condition.

One strong argument for the regression discontinuity (RD) design is that it allows for elimination of selection bias when implemented properly. In fact, in cases where a randomized design is not possible, a RD design is the recommended alternative to quasi-experimental and associational designs because it allows for an unbiased detection of treatment effects (Cook, 2008; Institute of Educational Sciences (IES), Technical Methods Report, 2008; Shadish, Galindo, Wong, Steiner, & Cook, 2011). The RD design is based on a pretest-posttest treatment-comparison group design, in which individuals are assigned to a treatment condition based on a cutoff score from a pre-intervention measure. Participants scoring on one side of the cutoff receive the intervention while participants scoring on the other side of the cutoff do not receive the intervention. As long as assignment to the intervention and comparison conditions strictly follows the cutoff criterion, any selection effects correlated with the impact of the intervention are also perfectly correlated with the pre-intervention measure, which, when held constant in the statistical analysis, allows for an unbiased estimate of the intervention impact on a post-intervention measure (Shadish, Cook, & Campbell, 2001; Thistlethwaite & Campbell, 1960; Trochim & Cappelleri, 1992). Consequently, researchers are starting to use the RD design to obtain unbiased impact estimates of education-related interventions when random assignment is not possible (IES, 2008). Like the experimental design, the logic underlying the RD design supports statistically valid conclusions, as evidenced by statistical proofs (Cappelleri, 1991; Rubin, 1977). In addition to eliminating selection bias, the RD design also avoids problems of regression to the mean presented by a cross-sectional analysis. Therefore, without selection effects and regression to the mean, the RD design avoids threats to internal validity that are inevitably posed by the cross-sectional design, making it a useful approach. (For a complete discussion of the RD design and internal validity, see Shadish et al., 2001).

### **A More Refined/In-Depth Approach to Understanding the Relation between Spatial Skills and STEM Performance**

To make further progress in understanding the spatial/STEM content relationship, it is important to move beyond establishing an association between performance on a spatial measure and global achievement measures for different STEM fields. In my view, this more fine-grained analysis is an important first step that should be conducted prior to the design of spatial

interventions within specific disciplines. For example, in a recently funded NSF proposal on the relation between spatial skills and middle school students' math achievement, we plan to address the question of whether a spatial/math association generalizes to math content as a whole or only to specific math content. Thus, we plan to investigate the relation between spatial skills and different types of mathematics achievement: **(a)** content likely to depend more on analytical, logical-deductive reasoning, and **(b)** content likely to depend more on spatial reasoning. This type of fine-grained approach may help to provide a clearer specification of the mechanisms by which spatial training could lead to improvement in different content areas with the specific STEM disciplines.

Secondly, when examining spatial skills, we need to develop more effective methods for identifying the strategies that students use when approaching spatial problem solving. For example, Geiser and his associates (Geiser, Lehmann, & Eid, 2006) developed a useful method for identifying individual differences in spatial strategy use by applying latent class analysis to identify groups of students whose response patterns were highly similar (making it possible to identify the strategies they used for solving the spatial problems). Then we need to use these methodologies to determine whether individual differences in spatial strategy use can be linked to variations in levels of performance on different types of content, concepts, and problem solving approaches within a discipline. Ultimately, it is important to determine whether changes in spatial strategy choice (e.g., moving from more analytical to more holistic approaches) are connected to changes and improvement in students' performance following spatial interventions.

# Implementing Spatial Thinking Across the College Curriculum

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The organizing committee's invitation to take part in this specialist meeting asked me to draw upon my experience developing educational initiatives at Penn State University and Esri. I did have the opportunity to play leading roles in the design and implementation of a half-dozen graduate and undergraduate programs during my university career. Now with Esri it's my privilege to observe and advise many more. When asked for advice about how to design a successful academic program, I point to the systematic program planning methods I found to be effective for forging consensus within and across disciplines (Cookson 1998). However, as I think about implementing cross-disciplinary spatial curricula I conclude that those familiar methods are not well suited to the problem at hand.

In light of other contributors' position papers and related research, the ideal outcome I envision for this enterprise is not to establish a discrete academic program or curriculum. Instead it is to infuse throughout the general education curriculum learning activities that foster "spatial abilities" (however defined). Is it too far a reach to imagine that spatial abilities might someday be including among the overarching objectives of several leading institutions' general education programs? This is one trait of what colleague Tom Baker and I have called "the spatial university" (Baker and DiBiase 2012). Though a few higher education institutions can reasonably claim to be "spatial universities" (in his position paper, Don Janelle states "UCSB is spatial"), none to my knowledge has succeeded in "spatializing" its general education curriculum. This, I believe, constitutes a grand challenge.

Beyond tried and true program planning models, it's instructive to look at lessons learned in earlier "across the curriculum" movements. One with which I have some experience is the effort to establish ethics across the curriculum. Three lessons learned in that movement seem germane here:

- 1 "Micro-insertions" of ethical contexts into existing domain-specific learning activities may be more effective than stand-alone ethics classes, extended ethics modules, guest lectures, or extra-curricular activities for infusing ethics broadly across the curriculum (Davis 2006);
- 2 Subject-matter experts may be more effective than specialists in teaching ethics within a particular discipline, though non-specialists must be taught how to teach ethics (Davis 2002); and
- 3 Achieving (1) and (2) require institutional commitments to provide sustained interventions by specially qualified staff at established resource centers. Several of the institutions represented in the specialist meeting have centers of this kind.



Lessons learned from “ethics across the curriculum” may be applicable to the spatial thinking movement. However, important differences in context must be kept in mind. One is that ethics education has had the most impact in professional programs like business and engineering, whose curricula are subject to accreditation by organizations like the Association to Advance Collegiate Schools of Business and the Accreditation Board for Engineering and Technology. A few institutions—including Penn State—have even mandated formal ethics training for all graduate students (Pennsylvania State University 2012). Corresponding mandates to incorporate spatial thinking don’t exist, and seem unlikely to arise in the foreseeable future. Absent such a mandate, the greatest impediment to implementing spatial thinking across the curriculum will be this community’s ability to demonstrate its benefits. As other position paper authors suggest, a good place to start may be to define spatial thinking broadly and clearly, and to identify and fill gaps in the relevant research.

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## Making a Place for Space

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Spatial thinking does not exist across the college curriculum and in fact, it does not explicitly exist in the college curriculum to any significant degree. The challenge, therefore is to make a convincing case that spatial thinking must be taught to all students, not just college students but K-12 students as well.

In the realm of non-profit organizations, case statements are core documents in a fundraising plan and its associated strategies (Ross and Segal, 2009). Case statements play multiple roles. They provide the rationale and justification for fund-raising campaigns, specifying pressing needs and providing supporting evidence for those needs. They identify benefits in terms of positive outcomes and the negative consequences of a failure to act now. Of the many keys to a successful case statement, three are particularly relevant to our concerns. Need statements should be: (1) strongly linked to clearly specified benefits, (2) focused externally, not just internally, and (3) thus targeted to people and places that can make a difference.

The overarching goal of this meeting is to develop a research agenda that will provide the evidential basis for the benefits underpinning the need statement. I want to focus on the second and third keys for a successful case statement. The focus on the external audience is a direct consequence of my experience over three decades as an advocate for another educational need, that of understanding geography. Whereas there the educational target ranged between preschool and grade 12 and here the focus is on college, many of the challenges are going to be the same.

I want to set my comments into two frameworks. The first involves a historical look at past efforts that relate to, if not exactly duplicate the thrust of our basic premise. The second involves an understanding of the structural contexts into which spatial thinking would have to be accommodated. Underpinning both of these frameworks are some current ideas about the production and reproduction of knowledge.

The ideas are based in part on two fascinating books. The first, by Ian McNeely and Lisa Wolverson (2008), is *Reinventing Knowledge: From Alexandria to the Internet*. The second, by Katy Borner (2010), is the *Atlas of Science: Visualizing What We Know*. This atlas comes from the *Places & Spaces: Mapping Science* project. Both books address the structure of the knowledge enterprise, directly in the case of McNeely and Wolverson and indirectly in the case of Borner.

Daniel Burnham, the great 19<sup>th</sup> century urban planner said: "Make no little plans; they have no magic to stir men's blood and probably themselves will not be realized. Make big plans; aim high in hope and work." Make no mistake about it: we are asking for structural and indeed radical changes at all levels of the American education system.

Building the case statement requires following a series of steps: (1) identifying the structural

challenges that we face in getting spatial thinking into the curriculum; (2) looking for models of other attempts to achieve structural change; (3) looking for models of programs that have achieved structural change; (4) evaluating parallel attempts to those we are proposing here so that we can either build on them or learn from their successes and failures; (5) finding a basis for the case statement; and (6) identifying an entry point into the current system that will permit structural change. What follows is a list of some of the ideas relevant to each of these steps.

- (1) The structural challenges are three-fold. First, space as an intellectual topic is not, and never has been, a focus of the American college system. Teaching and research about space, defined broadly, are fragmented across disciplines ranging from philosophy to physics, mathematics to statistics, and architecture to geography. Second, colleges and universities are epitomized by stove-piping. Disciplines are fiercely resistant to any type of change that might appear to threaten their territory and therefore existence, especially if another discipline might be a beneficiary of that change. Third, there is, as yet, no natural constituency in the world at large that might support an attempt to build spatial thinking into the curriculum. Spatial thinking is inherently cross-disciplinary: where does it fit?
- (2) There have been two major attempts to change knowledge structures at the collegiate level, one very successful and the other less so, at least as yet. In the period from 1990 to 1999, the *Decade of the Brain* was an effort "...to enhance public awareness of the benefits to be derived from brain research" through "appropriate programs, ceremonies, and activities." Part of the current success of the neuroscience community might be attributed to this highly effective campaign. From 2000-2010, the Decade of Behavior attempted to achieve similar goals for behavioral research. What can we learn from such efforts?
- (3) There are college-based programs that have successfully reshaped fields and had cascading effects on everything from collegiate structures for teaching, to research, to popular understanding. One prominent example is the *National Center for Atmospheric Research* at the University of Colorado (Boulder). It helped in the shift from the concept of meteorology to the idea of atmospheric sciences and has played a leading role in advancing understanding of global environmental change. Closer to home, the *National Center for Geographic Information and Analysis* (NCGIA) has also been successful. What can learn from such programs?
- (4) Over the past fifty years, there have been various attempts to bring the idea of space to the forefront, in some cases deliberately so and in others accidentally so. Included in such a list would be Balchin and Coleman's advocacy of graphicacy; the development of regional science; the development of science, technology, and science programs; and the idea of multiple intelligences (one of which involves space). What can we learn from the successes and failures of these ideas?
- (5) In the K-12 educational realm, there are typically three rationales for a place in the curriculum: economic via the development of human capital, intellectual via the idea of equipping someone for life-long learning, and social via preparation for civic participation. Can we use these same three rationales and if so, how and on what basis?
- (6) There is an entry point into the college curriculum via the idea of general education. Given the roots of general education in the liberal arts (as originally defined under the medieval concepts of the quadrivium and trivium), there may be a way of getting spatial thinking accepted as being

as important to undergraduate education as are English and mathematics. How can we establish that spatial thinking is both central to and rooted in a longstanding educational tradition?

By considering each of these steps, we can build an effective case statement for spatial thinking that focuses on the external audience, recognizes both opportunities and constraints, and which draws on the experience of others as it attempts to create structural changes in higher education

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## Enhancing Spatial Thinking in Public Administration and Policy

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There is a growing need to expand a spatial analysis framework within fields of public administration and policy. Addressing a wide variety of public policy problems such as urban revitalization, public health, and hazard mitigation increasingly requires pulling together multiple institutions within a place-based framework. Management and policy training for public administration professionals has, however, often failed to build basic competencies in place management and spatial analysis that are increasingly required to address these cross-cutting problems. I briefly examine the emerging opportunities to expand spatial analysis in public administration and policy in two areas: instruction and research.

### **Applications for Enhanced Spatial Thinking Instruction in Public Administration and Policy**

Students of public administration are trained to understand the management implications of public policy decisions. Traditionally, training for public administrators has focused on the budgetary and personnel tools that managers can use to marshal resources to effectively administer public policy. This fairly narrow view of public management is increasingly being expanded to include training that emphasizes the governance challenges of administering public policy in settings where public, private, and non-profit actors work to solve problems. Many of these multi-actor settings focus on the spatial challenges of administering place-based policy (Orszag et al 2009) to improve specific places like cities, counties, or even neighborhoods. While place management concepts are emerging as important areas of concern for public administrators (Mant 2008, Leinberger 2012), traditional programs are struggling with how to incorporate spatial thinking into their undergraduate and graduate programs.

To address this situation, I have begun to build course material that seeks to build spatial thinking directly into the core public administration and policy courses that I teach. Encouraging students to understand that “policy happens some *place*” starts with building a spatial vocabulary. The first step in this process is to introduce basic images and maps that help to spatialize policy and help students begin to “see” policy concepts and understand the physical manifestations of policy decisions.

Carrying out this initial phase of the spatial analysis approach is fairly straightforward. I assign readings on the key policy concepts as usual. Instead of immediately jumping into a discussion of abstract concepts, I begin with a series of images that help to show physical manifestations of the concepts. I walk the students through the images asking them probing questions about what they see. Students have an almost innate ability to explain what’s

happening in a particular landscape or image. Starting with an example like this can generate discussion and make it easier for students to make the jump to more complicated concepts. After they break down all of the key elements in the image, I then introduce the terminology that helps to define the concepts behind the image. As the semester continues this basic spatial thinking is enhanced with management concepts that stress the need to manage place for improved policy results.

This approach helps to tie core public administration concepts with more spatial fields of urban planning/design and geography. Advancing the teaching components that could help to build spatial awareness into the core of our undergraduate and graduate programs is an important need for our students and one that I'm excited to address through the Spatial Thinking seminar at UCSB.

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## Infusing Spatial Thinking Across the Disciplines: A Faculty Development Perspective

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Any effort to integrate spatial thinking across the domains of knowledge represented by the varied disciplines in a college or university must begin with a thoughtful faculty development plan. Becher and Trowler (2001) argued that faculty in higher education are actually members of different professions (he used the term tribes), and while they may share a common mailing address, the way they approach their work can differ dramatically from one department to another (or even within a department). These diverse perspectives must be considered as we work to make spatial thinking an essential element of higher education teaching and research. Healey (2005) noted that incorporating discipline-specific perspectives can also help bridge the gap between research and teaching; and as faculty consider the spatial perspectives that inform their own research, they can be more deliberate about making explicit connections in their teaching. An emphasis on active, inquiry-based learning can help transfer spatial perspectives across the void that sometimes exists between the worlds of research and teaching. A discipline-specific approach to professional development (with a particular emphasis on teaching) was adopted at several universities and leaders of faculty development centers found that such an approach led to more effective adoption of new and innovative teaching methods (Lenze, 1996). So as work progresses on this spatial thinking project, the development and diffusion of a wide array of discipline specific examples and case studies will help facilitate more widespread acceptance and adoption.

My personal background includes an interest in infusing spatial thinking in introductory-level college courses, and incorporating elements of active and problem-based learning into the undergraduate curriculum. Beginning in the late 1990s (as a consequence of nearly \$2 million in grants from the Pew Charitable trusts), I began to work with colleagues at Samford University to research and implement Problem-based Learning across our school's curriculum. In 2002, I served as co PI for the NSF-funded AEGIS (Academic Excellence Through Geographic Information Systems) Project. The aim of the AEGIS project was to provide professional development for university faculty in various disciplines who then developed GIS-based learning modules for their particular classes. Disciplines represented in the project included: History, Psychology, Biology, Classics, Sociology, and Geography. As we developed that project, it became clear that skills associated with spatial thinking were underdeveloped among program participants, and we had an unrealistic view that simply training faculty in the technical aspects of GIS would suffice as they developed their learning modules. Our initial faculty development strategy could be summarized as "show them how to use GIS, then stand back and wait for the magic to happen." But as faculty struggled to develop their modules, we began to realize that

technical skills were secondary to broader issues related to the way project participants conceptualized their problems. We discovered that many faculty found it difficult to conceive of a discipline-specific problem using a spatial perspective. In retrospect, placing a greater emphasis on spatial thinking would have enabled project participants to develop much more robust learning modules, and in turn, help their students develop spatial thinking skills. A progression from generic spatial thinking exercises and examples, to discipline-specific ones, could be followed by giving faculty an opportunity to develop their own modules (preferably peer-reviewed) that integrate spatial thinking into their own research, which can then be transferred through active learning to their own students.

One consequence of the project was a dedicated funding line to support a university-wide ArcGIS site license, and while we have maintained this commitment, we have found that few of the AEGIS project participants have continued to make GIS (and spatial thinking) part of their teaching and research. It is clear that we failed to incorporate a plan for sustained follow-up and support for project veterans. This is particularly important in light of recent advances in the theory and application of spatial thinking, and any effort to revive this project (or to develop new initiatives at any college or university) must include both explicit instruction in spatial thinking and a firm commitment to provide follow-up support.

The laudable efforts to make spatial thinking an essential part of a university education depend on faculty buy-in, and on extensive training and support. Without proper and sustained faculty development, any efforts to infuse spatial thinking across a college curriculum are bound to fail.

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### Web resources

- Discipline-Specific list of journals that focus on teaching  
POD Network <http://www.podnetwork.org/resources/periodicals.htm>



## How is Space Represented and Analyzed By Scientific Disciplines other than Geography?

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**S**patial literacy must deal not only with the human scales typically used by geography, but rather the full range of spatial scales in use across the sciences. The spatial scale continuum is typically divided into four distinct regions<sup>1</sup>: (i) subatomic, (ii) atomic to cellular, (iii) human, and (iv) astronomical. Many research disciplines use space (and time) as the primary means for organizing and analyzing their data and so have sophisticated conceptualizations to represent the objects and fields of interest. Examples are physics (at both sub-atomic and universal scales), nano-materials, computational chemistry, bio-engineering and drug discovery.

Thanks largely to the adoption of widespread computational modeling and simulation, all of these disciplines have mature software systems and tools (just as geography has GIS) that can themselves be scrutinized to reveal insights into how space is represented, navigated, manipulated and analyzed. This in turn should lead at least to a deeper understanding of the common ground and the unique approaches to spatial reasoning, and thus improve the design of learning materials aimed at a more general audience.

The approach taken here is to examine the computational systems that different disciplines have developed to represent and compute over space (and time), in order to understand the similarities and differences that these reveal about the conceptualization of space itself.<sup>2</sup> The opportunity to do so was created by working directly with these systems and engaging in active research with individuals from these user-communities over the last two years.

There exist many tools and techniques for representing the abstract mathematical properties of space, and for operating on contained objects independently of any assumed scale. For example geometry, topology, qualitative spatial reasoning and scale-space methods in computer vision are all branches of research that are often thought to universally apply across spatial scales.

Two motivating questions drive the work reported here:

1. Do the spatial concepts we might find in GIScience—such as Euclidean geometry, topology, projections and their related analytical functions—play important roles at all scales? And if so, how does scale (and discipline) affect the way they are used
2. Are there concepts and metaphors in use across other spatial communities that are not usually found in human-scale research such as geography and GIScience?

This research analyzes the representation of space within analytical and simulation systems used

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<sup>1</sup> [http://en.wikipedia.org/wiki/Orders\\_of\\_magnitude\\_\(length\)](http://en.wikipedia.org/wiki/Orders_of_magnitude_(length))

<sup>2</sup> This is in contrast to ethnographically-based approaches that work with a community (representatives from a specific culture or discipline) and use interviews, questionnaires or direct observation to surface up the norms of spatial understanding. The author of course acknowledges that his own understanding has also been also developed in part by interactions with researchers with whom he has worked.

by several different science disciplines, including: Star Mapping and Big Bang Cosmology at the astronomical scale along with Computational Chemistry and Materials Science at the atomic to cellular scale and also Bio-Engineering at cellular and human scales. These representations are contrasted with those used in (geographical) cartography.

The following list of concepts is used to derive a comparison between these disciplines:

- The representation of space as a container
- The reference frame(s) by which aspects of this space are brought into focus (such as projections)
- The representation of objects and/or fields within the space
- The role and form of topology and geometry in use
- The typical analytical tasks to be undertaken
- The number of data instances typically represented in the space

### **Summary of findings**

The findings show that each of the research communities described uses distinct computational models of space, which have evolved over time to better address particular domain-science questions. These models have many points of similarity, but sometimes imply a different conceptualization of space, and certainly a different degree of importance is given to specific spatial properties and relations. All the systems studied have geometric aspects, but these aspects do not always represent position, nor do they always describe shape and of course they are not all Euclidean. Some systems add topology, but not with the same goals as typical use in GIS. Perhaps the biggest difference is in the reference frames used to establish position, which vary profoundly between disciplines. Any researcher who wishes to understand or work with these models in detail will need a different set of mathematical skills, but there is—I believe—a core of spatial thinking skills that can be useful abstracted.

All the underlying systems investigated deal with large numbers of records and have sophisticated indexing and optimization strategies for search, retrieval and data compression<sup>3</sup>. There are some interesting concepts shared by two or more communities: The 'Lock and Key' metaphor used extensively in protein docking (drug discovery) has parallels in some of the spatial reasoning work reported in GIScience, since it utilizes complex (and often partial) shape descriptions; the positioning used in star mapping against reference stars with known trajectories is similar to the positioning strategies used in GPS (satellite derived) navigation. Discovering more of this common ground might be useful in shared educational approaches to spatial thinking and learning, particularly in readying scientists for spatial literacy at more advanced educational levels.

A summary of the different disciplines and systems described above will be presented, along with a summary table and comparisons to map cartography. Some conclusions will be drawn about what might constitute spatial literacy from a general scientific perspective.

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<sup>3</sup> As an aside, there is much that could be learned from these communities to help improve the efficiency of current Geographic Information Systems, particularly when scaling out to larger data collections and in the design of efficient spatial indexing methods.

# How Does Spatial Thinking Contribute to the NRC Framework for K-12 Science Education?

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How does the recent National Research Council (NRC) *Framework for K-12 Science Education, Practices, Crosscutting Concepts and Core Ideas* (2012) reflect the value of spatial thinking? Any NRC report on science education tends to be a barometer of how education experts in scientific disciplines in academia would like to see future pedagogy. Moreover, this national Framework, the first since 1995, serves as a basis for a future set of science standards in preparation by the National Science Teachers Association. Therefore it is important to consider how consistent it is with the goal of promoting spatial thinking in the undergraduate curriculum.

Advocates for the importance of spatial thinking across the undergraduate curriculum must promote the case that spatial awareness enables students to analyse and represent their understanding across domains. For example, The National Research Council (NRC) report on *Learning to Think Spatially* (2006) presented compelling examples of the significance of spatial thinking in discovery and understanding in the science disciplines, building the case those students in K-12 schools can improve their achievement in science by demonstrating spatial literacy. Has that argument been convincing for the panel members of this new report?

## The NRC Framework structure

The Framework, as the title implies, includes three main sections. Listed below are the main topics in the first section of the report. Both Practices and Crosscutting Concepts are presented before the third section on Core Ideas, countering the traditional focus on disciplinary knowledge as the key component of science curriculum. However, the report defines the word practice as a combination of skills and knowledge, thus reintroducing the importance of factual information.

### *Scientific and Engineering Practices*

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Clearly the focus on models (#2) assumes the ability to employ spatial thinking, especially as it includes 3D modeling. The report claims that students will learn how to ‘construct drawings or diagrams that represent processes or models’. However that statement is made without any explicit reference to the contribution of spatial thinking. Nor do any of the titles in this list address the role of spatial analysis in scientific and engineering practices.

### ***Crosscutting Concepts***

1. Patterns
2. Cause and effect: Mechanism and explanation
3. Scale, proportion, and quantity
4. Systems and system models
5. Energy and matter: Flows, cycles, and conservation
6. Structure and function
7. Stability and change

The list of Crosscutting Concepts includes several topics fundamental to the “Concepts of Space, Tools of Representation and Processes of Reasoning” that were outlined in the 2006 report and the fact that Patterns is the first on the list clearly seems to raise the profile of spatial thinking. Closer examination of this section raises questions about that link:

*Patterns: Observed patterns of forms and events guide organization and classification and they prompt questions about relationships and the factors that influence them. (p.84)*

Compare this brief outline with the analysis of the components of pattern observation listed in the NRC report on spatial thinking (Hochberg, 1978).

- Distinguishing figures from ground
- Recognizing patterns, both outline shapes and internal configuration
- Evaluating size
- Discerning texture
- Recognizing color
- Determining other attributes

This contrast may be explained by the fact that authors of this Framework do not focus on how K-12 students will learn the highlighted practices and crosscutting concepts, leaving that task to the group of practitioners who are charged with developing the new standards for science teaching.

However, the Framework does specify that students will be able to represent and explain scientific phenomena with multiple types of models and with accurate scale, proportion and quantity, assuming implicitly that somehow students will learn how to demonstrate those skills. This example illustrates how little of the specific focus of *Learning to Think Spatially* has made its way into this new document and presents a challenge to those who want to promote the value of explicit instruction on spatial thinking.

## Concepts and Principles for Spatial Literacy

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*\*NOTE: Much of the work discussed here has been undertaken with collaborators, including Donald Janelle, Daniel Montello, and Michael Goodchild, all of U.C. Santa Barbara*

Spatial thinking capability is strongly correlated with educational and professional performance in STEM fields (NRC 2006), but the systematic and integrative instruction of spatial concepts, principles and reasoning skills is not an explicit goal in K-12 curricula. Although educators do set standards for verbal literacy, numeracy and analytical reasoning generally, there has been no comparable articulation of what it means to be spatially literate. For this reason, estimating what spatial concept knowledge and reasoning skills we can expect of college freshmen is a challenge.

Perhaps it is the ubiquity of spatiality that prevents us from viewing spatial reasoning as a distinct practice, as we do mathematics, reading and writing. Borrowing a formulation from the NRC 2006 report, we think *in space* (e.g., navigating and wayfinding; proxemics), *about space* (e.g., the structure of objects and their distribution at all scales) and *with space* (e.g., diagrams and concept maps). Reasoning by spatial metaphor is arguably one of our most commonplace and powerful cognitive strategies (Lakoff and Johnson 1980).

In order to inform the design of a prospective college course in spatial thinking, we identified fundamental and trans-disciplinary spatial concepts in the context of the recent TeachSpatial project<sup>1</sup>; that is, concepts which are relevant to multiple science and engineering fields albeit with discipline-specific variation in perspective. This effort at “finding the spatial” included several initiatives over a two-year period:

- We examined twenty source texts that specifically enumerate spatial concepts from seven disciplinary perspectives<sup>2</sup>, and harvested the results and arranged them in a single lexicon.
- Using that lexicon, we measured ~240,000 NSF award abstracts for spatial term density, in part to demonstrate the breadth of spatiality across the Directorates, then validated the measure with an experimental survey to confirm its results corresponded to human judgments of spatiality in text (they did)<sup>3</sup>.
- We convened a specialist workshop of eight spatial experts from the fields of geography, cognitive psychology, geoscience, mathematics and education, in order to locate spatial concepts within US science teaching content standards for grades K-12 (NSES 1996)<sup>4</sup>.
- On the basis of that work, we refined our existing concept lexicon, then used it to locate existing teaching resources registered in the National Science Digital Library (NSDL)<sup>5</sup>

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<sup>1</sup> <http://teachspatial.org>, undertaken by the Center for Spatial Studies at UC Santa Barbara (NSF-DUE 1043777)

<sup>2</sup> The works were from geography and geography education (11), psychology (3), urban design (2), geoscience (1), mathematics (1), linguistics (1), and science education (1).

<sup>3</sup> <http://www.teachspatial.org/nsf-spatiality>

<sup>4</sup> <http://www.teachspatial.org/spatial-concept-terms-us-science-teaching-standards>

relevant to spatial concepts; the result is a set of resources for each concept representing perspectives and specific learning objectives of multiple disciplines (see the TeachSpatial *Resource Browser*<sup>5</sup>).

Our dual objectives in creating the TeachSpatial collection for NSDL were **a)** to demonstrate the breadth and generality of spatial concepts and principles; and **b)** assist instructors and curriculum developers in designing ways of making instruction in spatial concepts and principles more explicit. There has been considerable positive response, but not yet significant impact. In my view more progress awaits subsequent steps now in the works and described briefly below.

In current work with Donald Janelle, we are linking the previously “discovered” fundamental spatial concepts as components of fundamental spatial *principles*. We view this step as part of a larger process which is in a sense being undertaken asynchronously by a global community of interest. Although spatial literacy appears to be an uncontroversial goal, we note that what Nora Newcombe (2006) has observed remains true, “. . . we still don’t know exactly how to infuse spatial thinking throughout the curriculum.” For K-12, such an infusion could ultimately require explicit grade-level spatial learning objectives. Teaching content standards are numerous and it is difficult to imagine successfully introducing new, trans-disciplinary ones. A possibly more realistic goal is to develop and publicize a set of generalized spatial learning objectives that educators could choose to integrate informally into curricula at any level. To begin, we will first enumerate spatial concepts within principles and highlight where they appear in existing curricula.

In doing so we are making two presumptions: that general concepts are building blocks for general principles, and that just as general concepts can have distinctive interpretations within disciplines, so too can general principles. Arguably, there is no feasible scientific way to discover which spatial concepts are most fundamental, or in what proportion spatial principles may be composed of them. Instead we can proceed in something like a *Delphi* process, by proposing sets of concepts and principles based upon our own experience and understanding, putting them before spatial experts in the interested community of scholars and educators for review, and then revising them to reflect any consensus. We hope this will in time help shape a useful foundation for curriculum development.

### Principles and concepts

The following is a preliminary list of principles composed of fundamental concepts (*italicized*):

1. **There are multiple ways to consider and analyze space and spatiality**
  - 1.1. Two distinct spatial perspectives are those of continuous *fields* and of discrete *objects*.
  - 1.2. *Space-time* may be viewed as 3D + 1 (time) or 4D (everything is an occurrence).
2. **Patterns result from, and reveal processes; conversely, process explains pattern**
  - 2.1. The *location, arrangement and distribution* of things-in-the-world is a result of processes—“natural” (i.e., environmental and without agency), man-made, or both.
3. **Form follows function**

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<sup>5</sup> <http://nsdl.org>

<sup>6</sup> <http://www.teachspatial.org/resource-browser>

- 3.1. The spatial *form* of natural objects (*size, shape, structure, orientation, texture*) is strongly related to their function;
  - 3.2. The same holds true for utilitarian artifacts—if well-designed, function drives form.
- 4. Spatial context matters**
- 4.1. Natural phenomena—i.e., things and happenings—are significantly impacted by their surroundings (*environment or setting*), including *neighboring* things and any *networks or ecosystems* they are *part of*.
  - 4.2. Observations and analyses of phenomena have a *frame of reference*—spatial, temporal and thematic *bounds* for what is being considered. This concept is strongly tied to those of *scale* and *granularity*. Reference frames may be *global* or *local* in absolute or relative terms, and *representations* may be high-resolution or coarse and highly generalized.
- 5. Spatial dependence and autocorrelation**
- 5.1. Attributes of things that are near to each other tend to be more similar than attributes of things that are far apart; such similarity leads to assertions of *clusters, regions, neighborhoods, and kinds*. (A generalization of Tobler’s First Law of Geography, which asserts this at the scale of “places.”)
- 6. Distance decay**
- 6.1. The level of interaction between entities at two *locations* declines as the *distance* between them increases.
- 7. Spatial change**
- 7.1. A significant proportion of the phenomena we observe, measure, analyze, and seek to explain concerns spatial change: change of *position, form, orientation, and spatial identity* (splitting and merging, e.g.). The same holds true for many non-scientific (i.e., humanistic) fields.
  - 7.2. Things move. A great many natural processes at all scales are dynamic—fundamentally spatial and temporal: *diffusion, dispersion, transport, migration, erosion, radiation, etc.*
- 8. Representation and scale**
- 8.1. We reason about phenomena indirectly by means of representations, which include mental models, computational models and graphical artifacts. All are necessarily abstractions, and may be at any scale and corresponding granularity (level of detail).
  - 8.2. Our measurements reflect this, as do results of cognitive and computational reasoning.
  - 8.3. Representations are by their nature incomplete and therefore a source of error and uncertainty; while these cannot be avoided, they must be accounted for in both scientific and humanistic explanation.

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## Broadening Education in Spatial Thinking

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With the publication of the National Research Council report *Learning to Think Spatially* and the funding of a Science of Learning Center on spatial intelligence, there is increasing interest in questions of how to teach spatial thinking. There is now good evidence that aspects of spatial thinking can be trained (Uttal et al., in press). But in educating spatial thinking, what exactly should we teach? If we are to be most effective in educating spatial thinking, we need to first identify what we mean by spatial thinking.

So far, I believe that we have not thought broadly enough in our characterization of spatial thinking. We tend to view spatial thinking with the lens of our own disciplines, so that individuals from different disciplines mean different things by “spatial thinking.” For example, in my own discipline, Psychology, most research on spatial thinking has focused on spatial imagery and related processes that are measured by common tests of spatial ability (mental rotation, paper folding etc.), and much research on spatial thinking in Geography has focused on spatial analysis and the use of spatial technologies such as geographic information systems (GIS). These are important aspects of spatial thinking, but spatial thinking is broader than either of these. Although there are dozens of tests of spatial ability (Eliot & Smith, 1983), in developing these tests, there was no systematic attempt to first develop a taxonomy of spatial thinking processes. As a result, current tests of spatial ability measure only a subset of ways we think about space or think spatially. Similarly, geographic information systems represent a powerful technology for facilitating spatial thinking, and have been applied broadly across the college curriculum, but there are other spatial technologies, such as interactive visualizations, virtual models and animations that are also central to spatial thinking.

In my own research I have studied spatial thinking by examining domains of expertise that demand spatial thinking, and analyzing the types of tasks that experts in these domains have to accomplish, and the spatial cognitive processes with which students in these domains struggle. To date, my colleagues and I have examined aspects of spatial thinking in medicine (surgery, radiology, and learning anatomy), in meteorology, mechanical reasoning, physics, and in organic chemistry. Based on my research on complex spatial thinking in these domains, I have identified two basic components of spatial intelligence (Hegarty, 2010). The first is *flexible strategy choice* between imagery or simulation-based thinking and more analytic forms of thinking. The second is *meta-representational competence* (di Sessa, 2004), which encompasses ability to choose the optimal spatial representation for a task, to use novel external representations productively, and to invent new representations as necessary.

My research has examined only a small subset of disciplines in which people think spatially. I welcome the opportunity that this meeting will give us to examine the nature of spatial thinking,



across the whole college curriculum, in order to begin to develop a broad characterization of the nature of spatial thinking.

In working toward a curriculum for spatial thinking, it will be important to identify which spatial thinking processes and skills are applicable to several disciplines and which are specific to particular disciplines. Some aspects of spatial thinking, such as imagining spatial transformations and using spatial technologies are likely to be broadly applicable. Therefore, one possible strategy in developing a college curriculum is to identify aspects of spatial thinking that could be taught in foundational general education courses. On the other hand, there are important questions about whether spatial thinking can be taught in a domain-general way or whether it is best taught in the context of a discipline. For example, we now have good evidence that spatial thinking processes (e.g., mental rotation) can be trained (Uttal et al., in press), but there is limited evidence that this training transfers to performance in academic disciplines that involve spatial thinking.

I expect that one of the outcomes of this meeting will be a set of research priorities that need to be addressed in order to fill gaps in our knowledge about the nature of spatial thinking. However, there are already promising approaches to spatial education being implemented at several universities. In drawing on current best practices and a broad understanding of the nature of spatial thinking, I think we can move forward and consider how a curriculum in spatial thinking can best be implemented at the college level, while continuing to research the nature of spatial thinking and evaluate current approaches to spatial education.

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# Cognitive Mapping and Spatial Cognition

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In promoting spatial thinking across the college curriculum, it is useful to consider basic research on how spatial knowledge is structured and acquired, including individual differences in learning styles. The field of spatial cognition has had a rich history of examining how individuals acquire and use spatial knowledge. In this position paper, I examine three specific areas of spatial cognition: **(1)** the components of spatial knowledge, which form the tapestry of our cognitive maps, **(2)** the role of spatial tools on both facilitating and inhibiting the acquisition of spatial knowledge, and **(3)** the role of spatial collaboration through social platforms, including volunteered geographic information (VGI) systems.

## Nature of spatial knowledge

Spatial cognition has posited a number of different typologies for spatial knowledge and cognitive maps over the past 30 years. Landmark, route and survey knowledge remains a good first pass at how spatial knowledge is characterized, while more sophisticated understandings have shown argued that space is conceptualized differently at different scales from object spaces to environmental spaces (Mark, et al, 1999; Montello, 2009). Regions and landmarks are particularly critical for the conceptualization of environmental spaces, which both assist in learning spatial information, while at the same time lead to systematic distortions of perceived distances (Hirtle, 2011).

More recent work has looked at differences between indoor and outdoor spaces, with a particular focus on multi-level spaces (Carlson, et al, 2010). Together with previous studies, this research line demonstrates how the ontology of space remains an important research area for characterizing the heterogeneous nature of both space and spatial representations (Kuipers, 2000).

Our own lab has examined what are the “tricky parts” of directions (Hirtle, et al, 2010), as spatial communication is a complex process that involves matching the description of the environment with the physical environment. In human-to-human communication, this dialog might involve landmarks, road objects and topography, such “Turn left at the stop sign, just past the McDonalds at the top of the hill.” The ability to automatically extract landmarks, visible objects, and difficult navigational maneuvers is an open problem for the development of user-friendly navigation systems. As a more general principle, the communication of spatial knowledge is one that is difficult and complex, regardless of the scale or purpose of the communication.

## Spatial tools

Navigation through space is often accomplished by some kind of GPS-based navigation system. Recent studies have shown a curious paradox that people who use GPS navigation systems

become dependent on them for future navigation to the same location (Parush, Ahuvia, & Erev, 2007). This raises an interesting question about how technology can present accurate geographic information to a user, but at the same time support the acquisition of geographic knowledge. Ideally, the repeated use of the technology would increase geographic awareness, rather than leading to impoverished knowledge of the surrounding environment.

One general recommendation from the literature is to highlight the cognitive structures of landmarks and regions, which will facilitate the acquisition of spatial knowledge. Of course, unique or useful objects for identifying spatial locations will vary from region to region and depend on both cultural norms and the variation within the environment (Klippel, Hansen, Richter, & Winter, 2008). Ongoing work on geographic ontologies could provide a theoretical framework, but additional research is needed on how to automatically extract salient objects and how to best use those objects in the communication of spatial relations (Hornsby & Yuan, 2008, Mark et al, 2005).

### **Spatial collaboration**

The ability to use crowd-sourcing and other forms of volunteered geographic information (VGI) is leading to a new generation of spatial tools (Goodchild, 2007). For example, while it is theoretically possible to identify potentially safe and efficient bicycle routes in the United States from road network data, a more profitable approach might be to automatically track routes taken by bicycle riders over a period of time. This approach would generate the preferred paths, regardless of the underlying database constraints on the space (Panciera, Priedhorsky, Erickson, & Terveen, 2010). The explosion of crowd-sourced data along with the growing number of explicit VGI projects will lead to vast new data sources, many with an implicit cognitive bias, which can be mined for new and useful information.

### **Summary**

The role of spatial thinking in our educational system can be fostered through the continued use of spatial tools and spatial problem solving. However, fostering spatial thinking through use of spatially aware tools does not always transfer the spatial knowledge. The development of selective spatial tools that are used in combination with discussion, problem-solving and the exploration of space could be used to better foster spatial knowledge. The successful application of tools will most likely occur when the principles of underlying naïve geography and other limits of spatial cognition are directly addressed, along with the benefits of human-to-human spatial collaborations found in many current VGI applications.

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## Building Support Systems for Spatial Literacy

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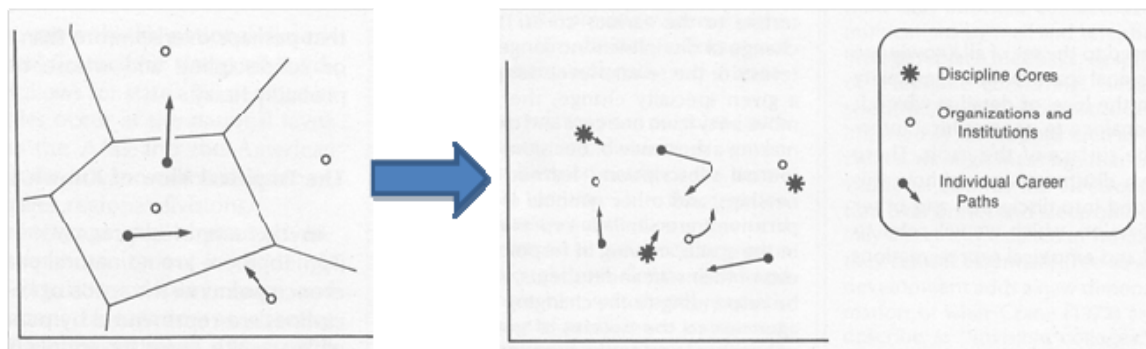
This statement is informed by experiences, which over time have broadened my outlook on the role of spatial reasoning and analysis across the academy. These include:

- research on career specialization within Geography, exposing literatures on innovation and socialization processes across a range of disciplines;
- involvement with the Center for Spatially Integrated Social Science (CSISS) and its role in the national dissemination of spatial analytic perspectives in the social sciences;
- development of web resources to access teaching materials about the nature and uses of spatial concepts across STEM disciplines; and
- trans-disciplinary initiatives to highlight the value of spatial perspectives for research and education at the university level.

These experiences are described briefly in succeeding paragraphs, each followed by a position statement about the potentials and possible strategies for introducing spatial thinking across the college curriculum at individual institutions and for education at the national level.

### A spatial perspective on knowledge specialization

The figure on the left (below) depicts the natural or administrative view of knowledge in which individual scholars seldom step outside the formalized boundaries of disciplinary departments, journals, and academic societies. In contrast, a more pragmatic view (on the right) is one where the intellectual cores of disciplines shift within the space of knowledge through time and individual career paths move freely in response to innovations and opportunities (Goodchild & Janelle, 1988).



**Position 1.** A trans-disciplinary specialization on the spatialization of knowledge and spatial thinking accords with a pragmatic perspective, drawing on expertise from a multitude of disciplines that contribute to and benefit from spatial methodologies for description, expression, explanation, and prediction. But there is a need to capitalize on the growing interest in spatial perspectives for research with: (a) educational initiatives that nurture spatial literacy and

*capabilities for spatial thinking, and (b) supportive infrastructure to promote spatial perspectives in career development.*

### **Dissemination of spatial analytic thinking**

The Center for Spatially Integrated Social Science (CSISS), with NSF funding, had as its fundamental mission the provision of infrastructure to support geographically informed spatial analysis across the full range of social sciences at the national level (Janelle & Goodchild 2009). CSISS played a pivotal role in the national dissemination of spatial analytic perspectives in the social sciences. It offered weeklong training programs to more than 1,000 early career professors, PhD candidates, and Post-doctoral researchers, developed tools for exploratory spatial data analysis (GeoDa), published examples of best practice (Goodchild & Janelle 2004), and built a website in support of these initiatives.

*Position 2. Documenting the need to enhance spatial literacy is a core undertaking that could justify a national effort, similar in scope to CSISS and the Spatial Intelligence and Learning Center (SILC), to provide essential training and resources for instructors to promote informed applications of spatial reasoning and uses of spatial methodologies. In the interest of trans-disciplinarity, examples should reflect humanistic understanding, artistic expression, scientific rigor, social relevance, and open access.*

### **The nature of spatial concepts and their uses**

TeachSpatial was supported by [spatial@ucsb](mailto:spatial@ucsb) and NSF to develop web access to teaching materials about the diverse nature and uses of spatial concepts across STEM disciplines. In 2012, <http://teachspatial.org> became an official site within the National Science Digital Library, providing access to nearly 3,000 teaching and learning resources that feature applications of spatial concepts in several science, technology, engineering, and math disciplines.

*Position 3. Drawing on the resources and expertise of TeachSpatial, the Spatial Intelligence and Learning Center (SILC), the GeoDa Center, and other initiatives that promote spatial thinking, it should be possible and beneficial to develop prototype syllabi and related teaching resources for general education and for advanced studies.*

### **Recognizing the trans-disciplinary value of spatial thinking in the college curriculum**

Since 2007, the Center for Spatial Studies has promoted the idea that *UCSB is Spatial*. A ThinkSpatial seminar series has featured more than 60 noontime presentations by scholars from more than a dozen disciplines; an undergraduate Minor in Spatial Studies was introduced in 2011, offering students customized advisory support in selecting from more than a hundred courses from 26 disciplines; and a one-unit Freshman Seminar on *Thinking Spatially in the Arts and Sciences* was initiated for fall 2012, with presentations by professors from seven disciplines.

*Position 4. Sustained initiatives in support of cross-disciplinary research and teaching enhance opportunities within institutions for collaborations in more ambitious undertakings. Thus, at UCSB, ThinkSpatial seminars built recognition about the role of spatial reasoning across the academy and contributed support for introducing a Minor in Spatial Studies. A centralized web resource to document such examples would be a valuable way to share experiences across institutions of*

*higher learning. Harvard University, Free University of Amsterdam, and the University Redlands come to mind as offering alternative exemplary strategies.*

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### Web links to Resources Mentioned:

- Center for Spatially Integrated Social Science, <http://csiss.org>
- The UCSB Center for Spatial Studies, <http://spatial.ucsb.edu>
- ThinkSpatial Brownbag series, <http://www.spatial.ucsb.edu/events/brownbags/index.php>
- Minor in Spatial Studies, <http://www.spatial.ucsb.edu/programs/academic-minor.php>
- TeachSpatial resources on spatial concepts, <http://teachspatial.org>
- GeoDa, <http://geodacenter.asu.edu>
- The Spatial Intelligence and Learning Center, [www.spatiallearning.org](http://www.spatiallearning.org)

## Giving Order by Space and Time

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Contextual information is key to the interpretation of data. For instance, research on information retrieval and recommender systems aims at extracting and inferring implicit information from a user's context to enrich queries. To give a concrete example, a search for *restaurant* using Google will first return recommendations for places that are open and in the user's vicinity before returning results on what defines a restaurant, e.g., a Wikipedia page. Thus, the result of such a query is determined by the user's location, the location of nearby Points of Interest (POI), the time the query is executed, and the opening times of potentially relevant POI. Additionally, modern information retrieval and recommender systems exploit additional contextual information such as the language setting on the user's device, the social graph of the user, previous searches, the current weather, and so forth. Reversely, this information can also be aggregated and used to learn properties shared by certain Points Of Interest. For example, bars are mostly visited during the evenings and clump together, while post offices are visited during working hours and are rather evenly distributed. Thus, types of POI can be distinguished based on such spatial and temporal properties. Similarly, personal information can be organized based on the user's location and time, e.g., to cache relevant information on mobile devices.

Abstracting from individual entities, space and time also influence how schema knowledge is defined. The challenge of handling local (i.e., not universal) conceptualizations at a global level is a prominent topic in artificial intelligence research since decades (McCarthy1987). The underlying idea is to be consistent at the local level but allow contradicting conceptualizations within the global knowledge base. For example, in context of the Kyoto Protocol, land use/cover changes have to be monitored. However, the participating countries have radically different classification systems. Approaches trying to resolve the resulting heterogeneity by standardization fail for political and geographic reasons, e.g., forests in Brazil are different from those in Greenland. One promising approach is to organize knowledge in form of domain specific *microtheories*. Each microtheory is defined as a coherent set of axioms and can be thought of as a single ontology. Different microtheories can conceptualize information about the same class but contain facts that are incompatible with respect to other microtheories. For example, one microtheory may be more precise and rigid with respect to physical properties and laws of nature, while another microtheory may introduce weaker constraints to support naive physics (Hayes1979).

Typically microtheories are organized in subsumption hierarchies. Facts specified in a specific super-microtheory are also true in each of its sub-theories. However sibling-theories can store contradicting facts. More formally, the hierarchy of microtheories is established through an antisymmetric, reflexive, and transitive generalization relationship. Surprisingly, alternative



ordering principles, e.g., based on space, time, or cultural aspects, have received little attention. As argued before many cultural, cognitive, and physical factors have impact on the categorization of geographic feature into types. This impact does not occur randomly but often follows gradually changing patterns. Thus, Tobler's First Law of Geography is also reflected on the schema level. For example, the definition of *river* changes gradually from northern to southern European countries. Similarly, temporal examples can be found in the domain of cultural heritage research which has to handle biased, incomplete, and contradicting information. Beliefs about the solar system from the Middle Ages have to be formalized in a different branch of the global knowledge base than microtheories conceptualizing beliefs from the Modern Age.

Consequently, space and time can be used to structure microtheories beyond simple subsumption hierarchies; see (Duce and Janowicz 2010) for a detailed discussion. The usefulness of such additional structuring principles can be demonstrated by contrasting the microtheory approach to monolithic schema standardization work, e.g., in the context of the European *Inspire* initiative (Infrastructure for Spatial Information in the European Community). For example, applying (administrative) containment as generalization mechanism between microtheories ensures that geographic feature types defined by states that are administratively contained by the European Union must be sub-types of EU wide definitions. Based on this requirement, instead of developing common schemas for all European member states top-down, individual conceptualizations from member states can be employed together with formal methods (e.g., Least Common Subsumer and similarity reasoning) to semi-automatically infer an appropriate common ground which does not violate local definitions. Thus, in context of data integration and semantic interoperability, if Spanish rivers, for instance, do not necessarily contain flowing water but rivers in Germany do, the computed common level for the European Union should not force flowing water as part of its river conceptualization (Duce and Janowicz 2010).

Summing up, the paragraphs above provide a brief overview how space and time impact information retrieval, recommender systems, as well as integration and interoperability on the data and the schema level.

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## Transitioning into a Data-savvy Adult

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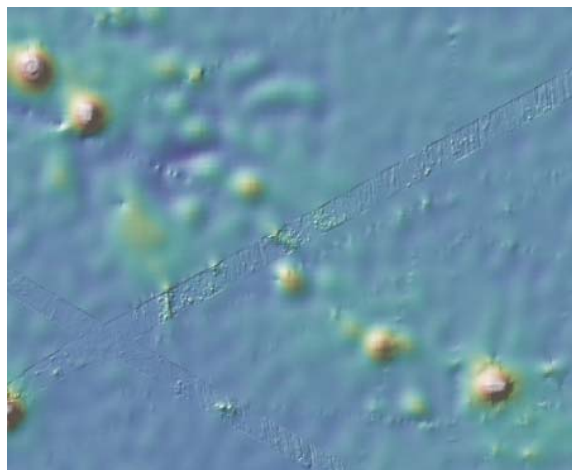
An important theme in my current work bears on how people make meaning from data visualizations. I focus particularly on data visualizations in which at least one of the spatial dimensions of the paper or screen corresponds to a spatial dimension of the referent system, in other words spatial data visualizations such as maps and cross-sections. I work in the domain of Geosciences, so the referent system I am dealing with is the Earth System or a portion of it.

The process of making meaning from data begins by perceiving and attending to distinctive patterns or regularities in the representation. Then, through some poorly understood process, the interpreter brings together knowledge and understanding of the referent system, metaknowledge of how data representations work (representational strategies), plus the information obtained by examination of the data representation at hand, to assemble an inference about the referent system (Figure 1). Two common forms of data-based inferences are about causality and about implications: why is the referent system the way it is? And given that the referent system is the way it is, what are the implications for humans or other actors in the system? Underlying this step must be a theory- or experience-based set of ideas about what types of patterns or regularities are likely to have significance as far as either causality or implication.

**Figure 1:** Making meaning from the data visualization of seafloor bathymetry involves going beyond just describing a flattish seafloor with bumps on it.

Observation of the visualization combines with knowledge of representational strategies and knowledge of Earth processes to enable a causal inference that the conical bumps are likely to be volcanoes and a linear trend is likely to be a hot-spot trace.

Spatial attributes, including shape, size and azimuth, are necessary but insufficient inputs to this process.



To my mind, the process of becoming skillful at making meaning from data must surely be a long one, extending over many years of education. Figure 2 sketches some key aspects that I think are likely to be part of a learning progression leading to an adult who can use data powerfully in professional or personal life. At first, students work with small data sets that they have collected

themselves, such as a map that they made of a stream near their school or a time series of lunar phase observations that they collected themselves. Later on, some students work with larger data sets of data that they did not collect, most often data obtained via the Internet. At first, they work on fairly well-defined problems, problems to which their teacher probably knows the answer. And then finally, they learn to work with large data sets around ill-defined problems, the sorts of problems characteristic of adult life.

**Figure 2:** Conceptual sketch of an educational trajectory that could lead to an adult who is able to make meaning from complex data sets in the context of ill-defined problems.

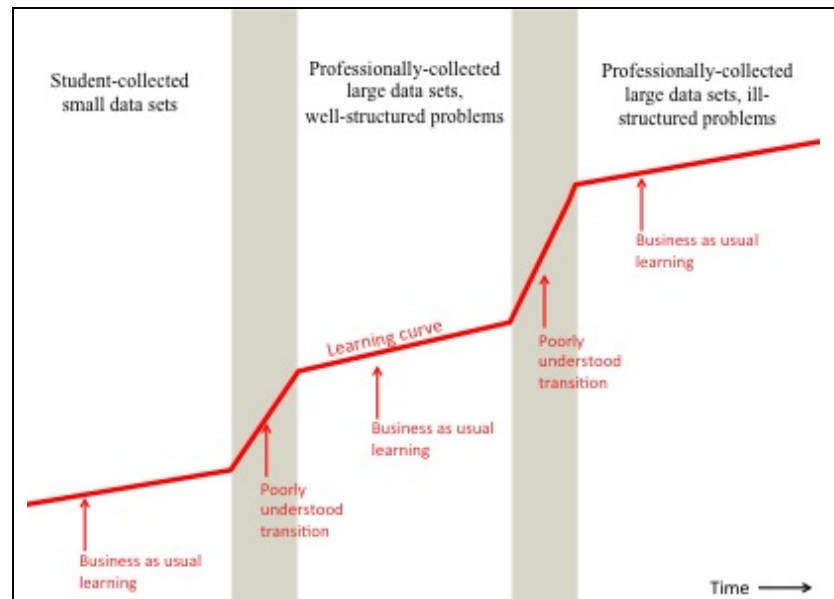


Figure 2 sketches this trajectory as having times of gradually increasing proficiency (labeled “business as usual,” when the learner is within one of these three domains, interrupted by poorly understood transitions, when the learner must make big steps in learning. Figure 1 is surely a simplification: we could expect that there would be some cyclic motion back and forth between domains and that an individual could simultaneously be in different domains with respect to different data types. But this sketch has helped me identify and articulate where there are likely to be sticking points in learning to make meaning from data, and where research could be most fruitful. How these transitions happen, and what kinds of curricular scaffolding and teacher professional development can help them happen, is a research agenda I would like to pursue.

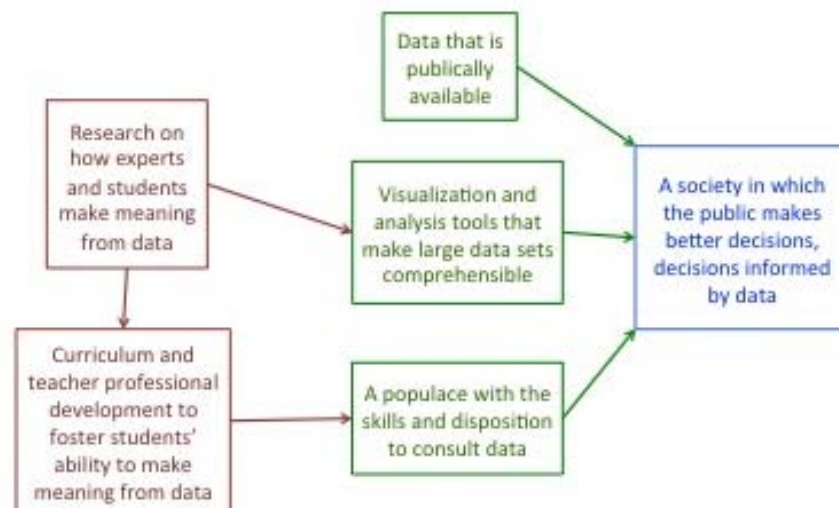
For Transition I, both the small-to-large and student-to-professionally-collected aspects are of interest. When students collect their own data which they subsequently interpret, they have had the full embodied experience of the environment of which the data are only a sparse, one-dimensional representation—the wind chilling their skin, a view of surrounding terrain, etc. But when they download data from the Internet, knowledge of context comes primarily from the thin description of metadata. Small data sets can be acquired and processed with simple, comprehensible technology (thermometer, paper and pencil, calculator), but larger data sets are typically acquired and processed with more opaque technology (satellite remote sensing devices; data visualization and statistical software). The up-side of Transition I is that it opens up

access to a wealth of additional Earth processes that were too big or too small, too old, too far away, too dangerous, or too expensive to understand through student-collected data. Transition I could happen as early as middle school, but it typically does not. Many students arrive at college having only minimal experiences in making meaning from data.

Transition II involves moving from the well-structured problems that are typical of formal schooling to the ill-structured problems characteristic of adult life. For well-structured problems, the materials and information needed to solve the problem are usually provided to the problem-solver or the paths to find the required materials and information are straight forward. But for ill-structured problems, the solver has to identify and then find the materials and information needed to solve the problem. In some cases, the solver may need data that don't exist and have to be acquired from scratch. In extreme cases, the instruments to collect the needed data don't yet exist, and need to be invented. For most problems encountered in formal education, including college, it can be assumed that the solver has or should have the skills required to solve the problem. But for an ill-structured problem, the solver may not have the skills required to solve the problem; the solver may not even know what the skills are that would help to solve the problem. An ill-structured problem might be set by nature or circumstances beyond human control or by complex social systems, and it is not known in advance that a solution necessarily exists. In a well-structured school problem, the problem was posed by a human being, typically by a teacher who underneath has the solver's best interests at heart, and the solver has reason to think that a solution to the problem does exist. College can provide an opportunity to foster Transition II, but there are still many people graduating from college without completing the trajectory of Fig. 2.

The stakes are high in figuring out how to move as many students as possible along this data-savviness trajectory, as we move into a more data-infused society. For individuals, ability to interpret data is becoming a workplace expectation in jobs ranging from refrigerator repair to teacher to healthcare provider. For society, we can hope for a society that makes better decisions, decisions informed by evidence ground in data (figure 3).

**Figure 3.** *The end goal of improving education around making meaning from data is a society in which decisions are more likely to be informed by evidence grounded in empirical data.*



## The Challenge of the Medium

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Spatial (and maybe in particular geographical) thinking is intimately linked to visual representations. Undoubtedly, maps are an inspiration for many students to turn to geographical sciences in the first place. It is also without question that many forms of visual information representation (maybe in combination with various forms of interaction) have the potential to enhance (spatial) concept learning, problem solving, and decision making. However, visual representations of spatial information are also often the cause of sometimes more, sometimes less serious spatial misconceptions. Examples of these misconceptions are:

- Distances within a city derived from subway maps. It is difficult to perceptually disentangle the fact that topological information as well as a course level of direction information (ordering information) is preserved in subway maps (at least most of the time), while (Euclidean) distance information is inconsistently distorted.
- Size of landmasses such as the often discussed confusion of the ratio of Greenland and South America based on the frequent use of the Mercator projection (rather than equal area projections).
- Direction information in relation to distance exhibited by the example of calculating ranges of missiles from a country where iso-distances change from circles to ellipses at larger distances (on most maps).

While the latter examples are related to mathematical properties of projections, the first one is based on design choices. The latter two can be resolved by using visual representations that are providing the “correct” information by either changing the projection (e.g., using the Petersen Projection rather than Mercator) or by overlaying maps with correct distance information rather than letting users interpret the maps themselves. To address the issue of distorted information through design choices some Australian maps use the label “Not Drawn to Scale” to warn their users for over-interpreting the visually represented information, and in our own work we discussed the use of grids to provide additional distance information.

The short lesson from these examples is, however, that once something is represented visually and is in violation of the clear and straight forward Euclidean properties of the medium, it is rather difficult to resolve this perceptual conflict. This list can easily be extended to examples of representing things that are not there, underspecified or vague, or multidimensional in nature. Overcoming the constraints of the medium is a challenge in many situations; if concepts (theory and map) are misaligned the characteristics of the medium will dominate.

To make things even more complex, we find similar misconceptions when we relate statistical analysis (modeling results) to visual representations. Statistics/spatial analysis, especially in the Big Data age, should be a central part of spatial thinking. We find, for example, that several basic concepts of what makes spatial special (e.g., Tobler's First Law of Geography, TFL; spatial interaction effects) find their way into main stream spatial products (e.g. ArcGIS, GeoDA) through their statistical grounding (e.g., spatial autocorrelation analysis in case of TFL). One of the main problems here is the understanding of the concept of randomness. While this is a problem in classic statistics, too, I find it is even more pronounced in the area of spatial thinking due the craving of the human information processing system to find and perceive meaningful patterns. Several textbooks<sup>1</sup> use drawing exercises to demonstrate to students that if asked to create a random point pattern, they will fail in most cases: Instead of a random pattern that shows both dispersion and clustering, students tend to create dispersed patterns by placing dots homogeneously on the sheet of paper (they fill the empty spots). This example is a valuable exercise, and from student feedback, it is an exercise with educational value. However, it does not change that students remain prone to seeing patterns where there is simply randomness.

A second related aspect of interpreting spatial information statistically is that humans bring heuristics and biases to the task. This topic has received attention since Tversky and Kahneman's article on decision making under uncertainty<sup>2</sup> and decision making with maps should not be an exception. A simple example from our own research<sup>3</sup> may document one aspect of these heuristics in relation to statistical concepts: If students (with or without formal training in spatial analysis) are asked to indicate whether a spatial pattern that consists of two colors (e.g., an election map) is significantly clustered with respect to one of the two colors (but not the other), the actual level of statistical significance is not playing a role in their decision making; in contrast, students focus on other aspects such as which is the dominating color to make their decisions ignoring that frequency of a certain color can independently vary from the statistical significance of that color.

### **Disruptive visualizations**

I believe that most students entering college have already acquired numerous misconceptions about space through the use of various types of media. I would like to envision a book or a course of spatial misconceptions that would provide plenty of examples to challenge people's views of the relation of visual representations and what they represent. The important point of this book/course would be the aim to bring theoretical concepts in line with the visual

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<sup>1</sup> Rogerson, P. A. (2001). *Statistical methods for geography*. London, Thousand Oaks, New Dehli: SAGE Publications.

<sup>2</sup> Tversky, A., & Kahneman, D. (1974). Judgement under uncertainty: Heuristics and biases. *Science*, 185(4157), 1124–1131.

<sup>3</sup> Klippel, A., Hardisty, F., & Li, R. (2011). Interpreting spatial patterns: An inquiry into formal and cognitive aspects of Tobler's first law of geography. *Annals of the Association of American Geographers*, 101(5), 1011–1031.

characteristics of the medium. This may not be possible for all spatial concepts, but, I think that such a collection would be of great value for all students interested in the spatial sciences. One reason I believe this is important stems from some previous research we did on the so called route effect<sup>4</sup>. This effect explains why cities locations learned from a map are memorized as being closer together than they are in case they are connected by a road: if there is a road, one can simply reach a city more easily and this aspect is assumed to guides how information is organized in memory. What we were able to show, however, is that this effect is also present while the map itself is present and it does not go away if the map is not introduced as a map but as a simply collection of blobs and lines. This simply demonstrates how strongly the characteristics of the medium influence our conception of spatial information and that this powerful medium, as mentioned in numerous books, has to be treated carefully. Some examples are already in practice, such as the above mentioned Peterson projection presented next to the (too) often used Mercator projection or the use of cartograms rather than standard choropleth maps. However, the question how statistical concepts (or the results of models) can be adequately represented visually, is an open question.

Klippel, A., Knuf, L., Hommel, B., & Freksa, C. (2005). Perceptually induced distortions in cognitive maps. In C. Freksa, M. Knauff, B. Krieg-Brückner, B. Nebel, & T. Barkowsky (Eds.), *Spatial Cognition IV. Reasoning, Action, Interaction*. International Spatial Cognition 2004, Frauenchiemsee, Germany, October 11–13, 2004, Revised Selected Papers (pp. 204–213). Berlin: Springer.

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<sup>4</sup> McNamara, T. P., Ratcliff, R., & McKoon, G. (1984). The mental representation of knowledge acquired from maps. *Journal of Experimental Psychology*, 10(4), 723–732.

# Spatial Thinking Across the College Curriculum

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I have been using and teaching about geospatial technologies and spatial thinking for almost twenty years with a broad audience including K-12 students, pre- and in-service teachers, undergraduate students, and Master's students. I'm currently directing a large dual-enrollment program with high schools in Virginia, wherein students learn about geospatial technologies and develop spatial thinking skills as they pursue locally-based projects (and earn college credit for the experience). With the support of the NSF-funded Spatial Intelligence and Learning Center, and in collaboration with Dr. David Uttal and colleagues at Northwestern University, we are conducting a research study to determine the extent to which the use of these tools impacts students' spatial thinking skills. I've also co-authored or co-edited four books (one in production) of geospatially-focused collections of activities. I'm currently serving as the Interim Dean of the College of Integrated Science and Engineering and as a member of the Geospatial Task Force at James Madison University

**Perspective:** I give the background above to provide some context for my remarks. Much of my work has been focused on the geospatial aspects of spatial thinking and the case has been made by many for its value across the curriculum. I support that line of thinking and have been an active advocate on my campus for broadening the reach of geospatial technologies primarily in General Education classes so that geospatially-based thinking and analyses can be made available to a much broader range of students. In my new position as Interim Dean, I have the Geographic Sense program under my purview and I'm hoping to get more traction in developing a broader audience for this aspect of spatial thinking. As a part of my work on the JMU Geospatial Task Force, I've offered workshops to faculty members across campus to introduce them to these technologies and spatial thinking so that they might then engage their students. As a Task Force, we're brought together faculty from STEM disciplines and the Liberal Arts to facilitate projects like a digital Geospatial Commons to share and archive data. However, more clearly needs to be done to increase the reach of this genre of spatial thinking.

While this meeting is focused on the tertiary level, I don't think we can ignore K-12 education. What preparation do we need to provide pre- and in-service teachers to help them build their students' spatial thinking skills? What about students that have a rich set of spatial experiences in high school (like my Geospatial Semester students) – what opportunities might they need when they get to college (this is not just a theoretical question – the Geospatial Semester is seven years old and has sent ~1,500 students to higher education having already had a strong exposure to geospatial thinking skills).



I also serve as the Interim Head of Engineering and so have curricular responsibilities in that area as well. Engineers typically focus on a different kind of spatial thinking (working in 3-D, visualizing and mentally rotating 3-D figures, etc.). I'm an advocate for this kind of spatially thinking as well, especially with the increasing importance of 3-D printing in engineering design and manufacturing and the work of Wai, Lubinski and Benbow on the importance of spatial thinking skills to STEM success. We are still in the early stages of the development of our Engineering program (we're just four years old) and I've been encouraging faculty to consider how to build relevant spatial thinking skills. This particular set of spatial thinking skills tends to have less relevance across the curriculum, but they are important within a number of the STEM disciplines.

I have a number of questions that arise both from my own work and my observation of the work of others in this area. Perhaps some of these questions might get addressed in the meeting.

- It would be nice to have a community consensus on the definition of spatial thinking in these contexts that we can use to communicate the value of spatial thinking to the various interested parties. Do we have such a consensus definition?
- What strategies exist to spatialize (and keep spatialized!) the broader curriculum? I've watched Sinton's efforts at U. Redlands and the UCSB work, but the broad reach across campus of both of these efforts seems somewhat limited.
- What's the case to be made for administrative buy-in to broadly spatialize the curriculum?
- How do we assess our efforts and by what measures do we declare success (or failure)?
- How do we maintain faculty buy-in and spatial thinking skill sets in the midst of an increasingly transient faculty (note this is an issue in K-12 as well)?
- What is the goal of our efforts—everywhere/all the time or focused areas/as needed? Different stakeholders seem to have different opinions.
- What does the online environment offer in terms of activities to build the reach of spatial thinking across the curriculum? Do we have the right tools to support the different genres of spatial thinking?

As you can see, I have many more questions than answers, but I think my experience does have some relevance to this topic and I would enjoy the chance to participate in a discussion on these questions and others surrounding this topic. Thank you for considering me as a participant for this meeting.

## Spatialization before Specialization

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What children and youths learn in school forms the basis for their approach to society and to science. They gain first experiences in scientific thinking, in asking questions, in planning experiments and evaluating the results. To foster the role of spatial information in society and to support the development of spatial skills it is important to point learners early on to the transdisciplinary power of spatial information and spatial thinking. Equipped with such knowledge and competences, they enter college with a broader view of the role of space and time and can identify spatial information concepts in various disciplines, now that they can easily get access to a lot of spatially and temporally referenced data.

Spatial thinking and learning can be applied to basic notions of space, where a variety of categorizations are available. One can distinguish between figural, vista, environmental, and geographical spaces (Montello, 1993) and apply a plethora of spatial concepts to these (i.e., the selection presented at [teachspatial.org/concept-browser](http://teachspatial.org/concept-browser)). Several spatial concepts, i.e., referring to position, are being learned in (early) childhood: i.e., learning of distance, direction and orientation as part of the natural human development, as works of developmental psychologists show (Piaget, Tversky, Lyben, Newcombe).

Several activities at the Institute for Geoinformatics, especially in the GI@School Lab address these goals. In the Geospatial Learning project, we develop software to support spatial thinking by following the known principles to foster orientation, way finding and map understanding skills. We combine them with user-centered design, game-based learning and situated computing and evaluate with different usability and spatial competence tests. We also develop projects for and with high schools, where students work with these and other geospatial technologies (i.e., GIS, GPS, Virtual Globes . . .) in a transdisciplinary context. A recent weeklong project with 80 high school students was, for example, about spatial information in history and archeology.

In these projects we realized that the more specialized concepts of spatial information (as opposed to just spatial concepts) are often too complex for high school students. A core selection of these concepts (Kuhn, 2012) enumerates Location, Neighborhood, Field, Object, Network, Event, Granularity, Accuracy, Meaning, and Value. High school students have bigger difficulties in understanding the technical notions of meaning, accuracy or event, sometimes just because of their lack in the mathematical background (logic, probability theory, abstract algebra). The learning and understanding of these concepts is therefore may therefore complement that of "classical" spatial concepts, but at a later stage in college.

**Position: Spatialization before Specialization**

Learning of concepts of spatial information across disciplines requires experience with spatial concepts and a solid mathematical understanding, so that it best fits the final phase of undergraduate studies, preceding or accompanying a specialization in domain concepts. To fulfill this educational position, we propose an advanced transdisciplinary undergraduate course on core concepts of spatial information. The contents will be aimed at undergraduate students with enough mathematical background and some associated knowledge and skills (i.e., in computing or cognitive sciences), preparing their further specialization in graduate studies.

The one-semester-long course (approximately 15 sessions) is planned as a cross-campus offer in the Spatial@WWU initiative (<http://spatial.uni-muenster.de>), where many institutions from our university have participated in a lecture series on spatial concepts in their disciplines in 2010 and 2011. It will introduce spatial thinking in the first sessions, taking into account the role of spatial information in each of the participating disciplines. The ten core concepts proposed by Kuhn (2012) will be the topics of the further sessions one by one, where the students will learn about similar and different forms these concepts take between disciplines. This learning will take place in discussions after prepared readings of associated literature. The rest of the time students will develop demonstrators or examples for application of the discussed concepts in different disciplines. The course format follows that of a similar course that has been taught to geoscientists and geoinformatics students over the past few years.

A collaboratively developed product will be a platform, similar to the concept-browser of [teachspatial.org](http://teachspatial.org), where the core concepts of spatial information are explained with several examples from different sciences and points of view. The examples will be provided as linked data in RDF to allow a linkage and further use and connections from other platforms and disciplines. As such, the course will foster inter- and trans-disciplinary work and a view on domains from another, spatial and temporal perspective. We expect positive effects on motivation due to the cross-disciplinary cooperation involving actual domain problem solving.

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# Spatial Education Across the College Curriculum: A Psychologist's Perspective

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It is both exciting and challenging to participate in a meeting attempting to design college curricula that will both enhance students' spatial thinking and attract support of faculty, students, and administrators. Having been asked to prepare a position paper from my perspective as a psychologist who has worked at the intersection of spatial thinking and science education, I offer a list of what I believe to be the most critical directions for our<sup>1</sup> collective work. Given space constraints, I amplify only the first three points, drawing on illustrations from my prior research.

**In take-home message form, I would urge that we should:**

- Identify overarching conceptualization(s) of space and spatial thinking that can provide the organizing structure for curricula.
- Draw on developmental theory and empirical research to identify spatial challenges. What is difficult for all children is likely to be difficult for a non-trivial number of adults.
- Partner with discipline-specific faculty (e.g., geographers, geologists, engineers) to identify points of contact and *test* hypothesized spatial-skill • discipline-mastery links.
- Establish and *test* the impact of instructional formats for enhancing disciplinary mastery via spatial education, e.g., pairing spatial and discipline courses, requirements, or assignments (as in "writing in the disciplines" programs).
- Replace the Faith-based School of Spatial Education with the Research-based School of Spatial Education as data (see above) allow. Despite demonstrated malleability of performance on specific spatial tasks, the current database is simply too limited to demonstrate the positive impact of a general spatial curriculum, identify necessary skill thresholds, etc.
- Consider (and *test*) the role of affective (motivational) as well as cognitive factors. As Evangelists of Spatial Education, we appear to assume that others need only be shown The Way and they will wish to join the fold. But to the degree that students see themselves as weak in spatial skills, hold essentialist views about spatial abilities, find spatial challenges uninteresting or even aversive, and see little self-relevance, they may be an unreceptive audience. We must evaluate outcomes of a spatial curriculum in relation to students' initial interests, beliefs, and goals; study if and how these change with instruction; and modify programs as needed to respond to observed student diversity.
- Address the developmental pipeline. A college spatial curriculum cannot ignore the filtering and educational processes that determine who matriculates and with what entry-level skills and interests. Insights from work involving primary- and secondary-school students may inform college instruction, could lead to strengthening pre-college spatial education, and might ultimately result

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<sup>1</sup> Throughout this essay, the first-person collective refers to the community of spatial educators and scholars

in establishing spatial prerequisites or entry-level placement tests like those required for other skill sets (e.g., mathematics; writing).

**Brief amplifications and illustrations of the first three points:**

*Spatial conceptual systems.* The goal of designing a curriculum to foster an understanding of “space” and enhance “spatial skills” requires identifying what these terms entail. I would suggest that there is a too-common tendency to equate space with location, and to equate spatial thinking with analyzing phenomena in relation to geographic location. Spatial thinking is more than this. Arguably one of the most important steps we can take toward the goal of facilitating students’ spatial thinking is to establish one or more overarching conceptualizations of spatial concepts that students should master. To illustrate, consider Piaget’s argument that children first construct topological (T) concepts and later, in tandem, projective (P) and Euclidean (E) concepts. Leaving aside controversies about sequence, the TPE proposal carries implications about tasks that should pose interrelated challenges, exercises that should advance mastery, and contexts in which transfer should occur. Although I would not argue for this system in particular, I would argue for some overarching system (e.g., see Manduca & Kastens, 2012; National Research Council, 2006) to organize curricula and avoid instructional approaches that are random collections of spatial skills *du jour*. An integrated conception of space might also be used to foster students’ spatial *meta-cognition* (e.g., practice analyzing how a particular task taps general spatial concepts or models might in turn promote students’ recognition of parallel spatial demands of a new task, thereby aiding transfer).

*Developmental insights into spatial challenges for adults.* The above approach led Piaget to devise various projective and Euclidean spatial tasks. Although he implied effortless and universal mastery by late childhood, later researchers discovered that adults also err. Illustrative are findings on the water level task (WLT) which asks respondents to draw lines inside tipped bottles to show water positions. Even some adults fail to represent the water as invariably horizontal (Liben, 1991), an error interpreted as indicating the person’s difficulty in establishing and using stable axes (e.g., the horizon) in the face of distracting referents (the bottle’s sides). These data suggest that some college students need to develop greater facility with coordinate axes, and, more generally, with frames of reference (FOR) (e.g., constructing FORs, identifying alternative FORs, relating multiple FORs, selecting among FORs).

*Interdisciplinary partnerships.* I use collaborative work with geologists to illustrate links between spatial concepts studied by developmental psychologists and college students’ science learning. In one study (Liben, Kastens, & Christensen, 2011) we hypothesized that students who performed badly on the WLT would have difficulty learning the geological concepts of strike and dip (requiring identification of horizontal and vertical axes in non-orthogonal contexts). Pretests identified college students with excellent, moderate, or poor WLT scores who were then taught about and tested on mapping an outcrop’s strike and dip. As hypothesized, strike and dip accuracy varied across WL groups (as did the use of observational strategies and accuracy in pointing to North). In another project aimed at synthesizing cognitive and Earth science, we (Liben & Titus, 2012) examined the spatial demands and skills entailed in a narrative description

of a day of a structural geologist's fieldwork and discussed implications for educational directions. Both studies have implications for spatial curriculum.

**Beyond this position paper:**

Although it is impossible to develop the full set of take-home messages here, I hope that the list provides some useful topics for our collaborative discussion in December. Information on cited references follows.

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## Spatial Thinking and the College Curriculum

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Visual forms of learning are crucial in many disciplines across the college curriculum. Our research shows that approximately half the space in science textbooks is allocated to visual and spatial representations such as diagrams, figures, photos, and tables. In addition, graphics (including animations, video, charts, photos, and illustrations) are heavily used in classroom instruction, often within the context of slide shows.

For the past 20 years, my colleagues and I have been investigating the most effective ways to present graphics and words to promote learner understanding. One of our earliest findings was that college students learn more deeply from a lesson that contains words (e.g., printed or spoken text) and graphics (e.g., illustrations or animation) than from words alone. However, not all graphics are equally effective in explaining material to students. We have conducted more than 100 experimental comparisons involving ways of presenting words and graphics to learners. This work allows us to generate a set of research-based principles of instructional design for multimedia learning—that is, learning from words and graphics. These principles are summarized in *Multimedia Learning: Second Edition*, and have relevance for improving instruction involving graphics across the college curriculum. I am particularly interested in how to design textbook lessons, slideshow presentations, and computer-based lessons using graphics and words that promote deep learning in college students.

Although we expect students to be able to learn with pictorial representations, we rarely teach them how to do so. Unlike mathematical and verbal skills, which are the focus of extensive explicit instruction in education, spatial skills often form part of the hidden curriculum—content that students are expected to learn without instruction. To address this issue, my colleagues and I have been investigating teaching of learning strategies for processing graphics and text. Students who do not develop effective strategies for processing graphics may need direct instruction in comprehension of graphics, analogous to widely implemented instruction in strategies for reading comprehension that focus on processing of words. I am interested in promoting this 21<sup>st</sup> century skill of how to mentally represent graphics and use them in spatial thinking.

# Spatial Thinking Across the College Curriculum

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The nature of space, spatiality, and spatial thought are all near and dear to my professional heart as a researcher and teacher (I even ponder them when I'm off duty!). It is clear that these topics find their way into the materials of a broad array of college courses, typically implicitly. In the context of this Specialist Meeting, five issues strike me as particularly important and interesting:

(1) **Generality.** What are the prospects for teaching spatiality explicitly as a distinct and general topic or skill as opposed to teaching it within the context of particular topic domains, such as physics, geometry, geography, and literature? Recent research documents that spatiality is found across the disciplines, including natural science and math, social science, humanities, and arts. Research has also been exploring the nature of spatial concepts and skills both within and across disciplines. Is there a modestly sized set of general spatial concepts and skills that transcend disciplinary and topical boundaries? Or are such concepts and skills inextricably bound up in specific topical or disciplinary domains? Is a hybrid approach optimum that identifies spatiality within domains but explores its generality across domains? For example, should we explore the meaning and use of the concept of "distance" within physics, economics, transportation, and sociology, and then explicitly compare it across these disciplines?

(2) **Scale.** Are there spatial concepts and skills that are general across scale (size), treated either as discrete classes or a continuum? Montello and Golledge (1999), in their report on a Project Varenus Specialist Meeting, discussed minuscule, figural, environmental, vista, and gigantic spaces. They claimed that spatial cognition and behavior are at least partially distinct within these scales, and a variety of theoretical and empirical arguments provide some support for this idea. For example, humans interact with and apprehend spatiality at different scales with different sensorimotor systems, and some research finds that pictorial psychometric spatial tests do not measure environmental spatial skills (such as wayfinding ability) very well. Is spatial scale an important or even necessary basis for distinguishing types of spatial thinking in an educational context?

(3) **Geometry.** Montello and Golledge (1999) further distinguished figural space as either pictorial or object space. How important is it to recognize distinct spatial concepts and skills as a function of the dimensionality of space? Also, spatial thinking is thinking about spatial properties, and those properties include both metric (or at least quantitative) properties like distance and direction, and nonmetric (qualitative) properties like containment and connection (technically, nonmetric geometries include not only topology but projective and affine geometries). How should the varying possible geometries be incorporated into spatial



education? Should we recognize that mathematicians might distinguish geometric properties differently than lay people do?

(4) **Spatial vs. Visual.** Historically, scholars from a variety of disciplines have tended to conflate “spatial” with “visual.” For example, one of the central dimensions of psychometric spatial ability is known as “spatial visualization.” As another example, people often conflate spatial thinking with mental imagery. But research is accumulating that “spatial” is psychologically distinct from “visual” or “imagistic.” It is likely that the role of spatial in some disciplines is primarily one of visual appearance. How should we treat this issue in the context of spatial education?

(5) **Time.** Finally, it is clear that temporality may be as ubiquitous and fundamental as spatiality is in reality and experience. Many researchers (for instance, in GIScience) repeatedly remind us of how fundamental time is, often going so far as to insist on terms like “spatio-temporal” instead of “spatial.” And don’t forget the insights of 20<sup>th</sup>-century physics. However, I see the conceptual clarity of an abstraction that recognizes stable spatiality (e.g., pattern) without dynamic change. True, unchanging reality might be nothing but an artificial abstraction, but that doesn’t mean it has no conceptual value. I think many applications of spatial thinking across disciplines are distinct from time and dynamics. Should this be recognized by those designing spatial educational curricula? Or should we insist on the involvement of time and dynamics at every turn?

## Spatial Thinking Across the College Curriculum

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In considering the plan for this Specialist Meeting, and the action agenda we are seeking to delineate, I think it is interesting to reflect on a prior report on an allied issue: the curriculum prior to college. *Learning to Think Spatially* (2006) was a landmark achievement, making a persuasive case for the importance of spatial thinking and its inclusion in K-12 education. It has succeeded in bringing spatial elements of education to the attention of researchers, policy makers and educators. I want to highlight three points about this report that seem to me relevant to the current meeting.

First, one of its key conclusions appears questionable in retrospect, namely the argument that spatial training of one skill rarely transfers or generalizes to other skills. Uttal, Meadow, Tipton, Hand, Alden, Warren and Newcombe's (2012) meta-analysis of this question (and other questions concerning spatial training) gives substantial reason to be optimistic about the generalizability of spatial education. However, note that we were only able to evaluate near and moderate transfer. Whether or not far transfer is feasible has not really been evaluated, and should be on the agenda for future research. Similarly, although we found evidence that training effects have some durability, the longest time intervals tested have been on the order of months, not years. Thus, we are missing some of the evidence we would like to have to plan and advocate for a college curriculum. We don't really have an answer to the question: *If a student is taught to imagine cross sections in the context of a geology course, does this skill transfer to imagining sections in engineering or biology?* In addition, the data base for the meta-analysis was too sparse to give a fine-grained answer to the question: *What is the role of technologies such as geographic information systems and virtual environment technologies in developing spatial thinking skills?* Some of the papers we reviewed used these technologies, and they seem to work. But we couldn't examine, how well, in comparison to what, for whom, or other more fine-grained questions. Research and educational policy will need to proceed in tandem.

Second, another conclusion of *Learning to Think Spatially* was that spatial thinking should not be a separate subject in K-12 education, but that instead, we should look to spatialize the existing curriculum. Within the context of the crowded day of the average American school, I think this plan is the only way to go, although informal education in preschool, after-school, museums and camps can perhaps take a different (and more direct) route. But college curricula are very different from K-12, allowing for substantial amounts of variety and student choice. So clearly we could offer a "spatial track" at the college level—but should we? Such an agenda seems to me quite different from supporting spatial thinking in existing disciplines such as geography and geoscience, entailing different pedagogical strategies and having quite different

implications for the organization of a university. In the “spatial track,” we seek to modify learners, making their spatial thinking more powerful. In teaching current curricula (and we should also include the other STEM disciplines), we may seek to modify the learning materials to make them more spatial, or their spatial content more accessible and transparent. I have discussed these two routes in a short commentary recently (Newcombe, 2012). Both ways of proceeding seem to me to have praiseworthy, but quite different, objectives. How can they be coordinated? Do they even need to be? I look forward to discussion of the inter-linked questions: *What are the connections between “spatial thinking” courses and curricula organized for disciplines? What are the administrative challenges and opportunities for implementing spatial thinking programs at the college level?*

Third, *Learning to Think Spatially* never really settled a question that has haunted the field of spatial cognition for a hundred years, and that no one has yet settled (for an overview of the history, see Hegarty and Waller, 2006), namely what typology of spatial skills makes sense? SILC has been using a typology that sharply divides thinking about objects from thinking about the environment, and that also distinguishes static representations and dynamic transformations within each type of spatial thinking. Thus, I think we can identify four component skills in answer to this question: *Can we identify a set of domain general spatial skills that are relevant to spatial thinking across several disciplines?* This typology also provides the framework I would advocate in response to this question: *What are the learning outcomes for spatial thinking curricula, and what form should assessment take?*

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## Spatial Thinking in Undergraduate Research

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This meeting comes at an opportune moment for me, as I take on the role of “GIS” program(s?) director at my university, and as a result I am keen to attend. The “GIS program” at the University of Auckland finds itself at an important crossroads in its development. This is brought on in part by local circumstances, but more significantly by changes in the meaning of a “GIS education” in the last 5–10 years, which are driven by (i) a need to consider what it means to think spatially in (quantitative) geography, (ii) the changing relationship of disciplines *other than geography* to GIS and allied technologies (GIS&T), and (iii) changes in the technological context.

### Thinking spatially in geography, or: back to the future (again)

In the contrarian fashion of a native of Belfast(!), it is a (rather informal and underdeveloped) pet theory of mine that the emergence of GIS from the mid 1970s into the 21<sup>st</sup> century has been to the *detriment* of a “thinking-person’s quantitative geography.” By contrast, I am constantly surprised at the rich seams of elegant spatial thinking that underlie earlier developments, in the *pre-GIS* heritage of geography. For all our present embarrassment of riches in data and toolsets, it is to Abler, Adams and Gould’s *Spatial Organization* (1970), or Tony Gatrell’s *Distance and Space* (1983), and the work of Tobler, Haggett, Golledge, Wilson and others that I turn for inspiration, when I consider what classes in “spatial thinking” might look like! Even allowing that the passage of time is required for “classics” to mature, this is a little strange! More optimistically, now that a geospatially-enabled world exists, and interested communities have time to step back from the details of designing and implementing the tools that now surround us, it seems like the stage is set for new classics in that earlier vein. I am therefore keen to be involved in thinking through what spatial thinking means both for tertiary education across the board (and for the analytical tradition in geography more specifically).

An idea that may hold some attraction in this context, is **a pattern language for spatial thinking**, drawing on the same general concept in architecture and software engineering, and building on the notion of “building-block” spatial models presented in my forthcoming co-authored *Spatial Simulation: Exploring Pattern and Process*.

### The changing relationship of disciplines outside geography to GIS&T

Any attempt to focus more narrowly on the pedagogic challenges within my own discipline, quickly redirects attention back out toward the “spatial turn” in disciplines ranging from Sociology and Economics to Archaeology and Zoology. For undergraduates in these and other disciplines, spatial thinking has become a critical component of their degree training. There is an urgent need to deliver appropriate learning opportunities to develop, both in a broad sense,

spatial thinking, and more narrowly, skills with tools that can enable such thinking (i.e., GIS&T). Yet relatively few academic staff in these varied fields are equipped to provide the grounding in modes of thinking and reasoning that this situation demands.

Most universities have struggled to handle the transdisciplinary scope of the spatial turn. With a few prominent North American exceptions (such as UCSB) there is rarely a critical mass of research-informed teachers to deliver the ambitious curricula developed variously by NCGIA and UCGIS. The more commonplace experience is of small groups of staff struggling to deliver cut-down versions of those curricula, while running the risk that their teaching is perceived as merely a “service” to colleagues in their own department or more widely. The widespread recognition of the importance of the spatial perspective across many disciplines offers a possible escape from these dilemmas, and I am keen to explore what it would mean to offer training in spatial thinking, both as a point of entry to more technical programs in GIScience, and as a service to other disciplines that could build on such a resource to provide more discipline-specific training in the particular facets of spatial thinking that are most important for them.

### **The technological context: teaching spatial thinking *without* GIS?**

The maturation of GIS software has made “lecture and lab” style courses in GIS increasingly difficult to deliver. The leading software package in the field has evolved from a single user desktop package into a large corporate network integrated platform. In this context, providing students from diverse, (often) non-computational backgrounds with more than a superficial exposure to available tools (“what button do I press?”) is challenging, if the industry-leading platform is adopted. Other tools (many of them free) are an attractive alternative, but bring their own difficulties, and may encounter student-resistance, given students’ understandable desire to develop marketable skills with industry-standard tools.

As recently as 15 years ago (when I completed my own Masters in GIS&T) the inadequacy of standard packages worked to their educational advantage! A limited range of interesting tasks could be accomplished with off-the-shelf packages, and study beyond entry-level required students to learn scripting, and as a seeming “by-product” to acquire spatial thinking (and technical) skills. Today’s tools are enormously more capable, but present the difficulty of finding an appropriate entry point, that focuses not on which toolbox to use or button to press, but on the critical spatial thinking skills that underpin those choices. Deciding what are the best current tools and environments to use to develop spatial thinking skills in the classroom and the lab, and more importantly, what principles underpin those decisions so that we can update those choices over time is a key challenge.

In recent years I have been evolving the courses I teach in spatial analysis to incorporate new tools (such as the R spatstat package, and GeoDa) rather than GIS packages, and it would be interesting and valuable to share those experiences with others facing similar concerns.

## Designing Better Methods of Instruction in Spatial Domains

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**M**y work has grown out of a background in behavioral research in spatial cognition and has been guided by the observation that instruction in many spatial domains can be significantly improved. My intention is to use my background to help provide improvements in instruction where they are needed. As I pursue this work, I find that I often emphasize different options from many of my colleagues in psychology. I think my own views arise from working in an area, instruction of basic neuroanatomy and neuroscience, that is a complex topic learned as part of relatively advanced disciplines. I will take these few paragraphs to try to express how my recent work has begun to define for me an approach to empirical work in instruction.

I am constantly reminded these days of the familiar tension between basic science on the one hand and ecologically valid research on the other. For my own part, I have grown rather impatient with the traditional model of hypothesis testing. I think that the many people encouraging Design-Based Research are pointing to contrasts that are important for the work I wish to do. A critical part of the contrast, in my view, is that science generally takes the world as it is and tries to analyze why it is that way. The approach leads to manipulating one variable at a time. Design-based approaches arise in the context of making new things. The first order of business is to measure how well the new systems work and to strive to make them better. Once best practices are established, we can move to analyzing precisely how and why the new systems work as well as they do. Whether you find this approach attractive will probably depend on your practical experience. In my experience, you cannot build an effective instructional system one variable at a time in a bottom-up fashion. The world has too many higher order interactions. You need to build the best system you can and compare it to realistic alternatives. Precisely why one system is better than another may not be immediately decided from the point of view of analytical theory.

My recent work has involved interactive computer-based systems with high quality computer graphics. Most recently, my colleagues and I have been developing systems for learning basic neuroanatomy. This work illustrates concrete aspects of my approach to instruction in several ways. First of all, I think that computer-based graphical systems will fundamentally change instruction in an area such as neuroanatomy. I am well aware of the research that suggests that such systems are not effective. The simple fact, however, is that well designed systems have not in general been constructed, and they certainly have not been tested. I believe that instruction in spatial domains will soon be transformed by new digital technologies informed by cognitive science and the long tradition of research on learning. Interactive computer graphics in computational instructional systems will permit exploration, thoughtful experience, testing, and feedback that was unimaginable until recently.

Another part of the approach that we have been taking is that the best way to develop skill in a complex domain such as neuroanatomy is to teach people the material in that domain. I am sure that there are many cases where it is a good idea to develop basic spatial skills, much as children learn basic mathematical skills. For complex material such as neuroanatomy, however, I think it is likely that we need to find the best ways of teaching that material. Each discipline will have its own tasks, its own complexities, and its own best solutions. The methods and solutions that are found to work well will generalize in many ways to instruction in other domains. But the development process must dive into the content of the domain in order to build those methods and solutions in the first place.

We have also been taking the approach that methods of instruction that work well for the typical person will work well for people who have low spatial ability. People who have low spatial ability may take longer to learn, but the methods that help them will be the same as the methods that help everyone else. This is not intended to overlook variations in spatial ability or to say that they are unimportant. Rather, it is a belief that a major source of variance in the effectiveness of learning follows from the structure of the domain. Finding a better way to make that domain accessible will benefit everyone.

Finally, I doubt that domains of spatial learning are homogeneous in terms of the kinds of knowledge and skill that they require. People learning to read microscope slides are not necessarily doing the same thing as people learning to read MRI images. Microscopes are applied to microanatomy, and this can only be seen through microscopes. MRI images concern gross anatomy, and most of the people who read them have had experience with dissection. Spatial localization is almost never important in microscopy, while it is often of particular importance for someone reading an MRI image. My guess is that the geosciences require knowledge and skills that are different from both of these biomedical cases. In this context, I am skeptical about whether the standard tasks from experimental psychology, such as the typical mental rotation task, are good models for the kinds of learning required in real world spatial reasoning. It may be useful to remember that before the advent of these “mental imagery” tasks, there was almost no scientific study of spatial cognition at all. After the advent of these tasks, many psychologists studied only these tasks. As psychology moves into areas of real spatial reasoning, I believe there will be a great deal to learn.

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## Spatial Thinking in Undergraduate Research

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Over the past several years, institutions of higher education have put increasing focus on experiential learning and extracurricular research experiences in the undergraduate curriculum. This shift has allowed students the opportunity to move beyond traditional text-based learning activities to modes of learning that employ embodied, exploratory methods of inquiry. Spatial thinking is one of the key components involved in active inquiry, and research in almost any field involves some aspect of spatial thinking. For instance, many of the activities involved in lab-based research, such as manipulating objects in space and understanding physical cause-and-effect relationships require spatial thinking. Similarly, in simulation-based research students often work at a spatial scale that is different from the scale of the actual objects or phenomena. Spatial phenomena may also be represented more abstractly, as numbers or variables with no real-world spatial correlate. Other types of research methods in the humanities and social sciences also make use of spatial thinking, often by using space as a metaphor in order to help give structure to abstract concepts or phenomena.

When considering spatial thinking across the entire undergraduate curriculum, several important issues must be addressed. While it is clear that undergraduate research experiences encourage the authentic use of spatial skills and processes, many traditional classroom activities, like listening to a lecture, taking notes, or reading a textbook are less likely to engage students in spatial thinking activities. As we work to bridge traditional classroom activities and authentic research experiences, we should consider how we prepare students to engage in hands-on research, especially with regard to how they are asked to negotiate the spatial processing their research requires. Rather than taking a particular stance on how this should be accomplished, I pose the following questions in an effort to stimulate discussion:

- How similar are the spatial processes involved in traditional text-based learning and authentic research experiences within a single discipline? For instance, could the embodied and physical components of an authentic research experience help a student struggling to understand traditional text-based materials?
- Can (and should) the spatial thinking requirements of a discipline be explicitly conveyed to students in order to prepare them for an authentic research experience?
- What effect do research tools (e.g., software, equipment, and instruments) have on spatial thinking processes involved in conducting undergraduate research?



## Spatial Thinking and Reasoning Across the Curriculum

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One of the great dichotomies in the anecdotes of education is between those students who are more math/science oriented and those who are more language/humanities oriented, and these kinds of distinctions appear to begin very early. As a scientist interested in individual difference in spatial cognition, I find that there is a general impression that my work is mostly (if not only) relevant to the former category of math/science learners. However, spatial reasoning can be found in nearly every discipline: organic chemists visualize isomers, writers organize words and sentences into coherent paragraphs, artists capitalize on 2D cues to offer the impression of 3D structures, and the list goes on. One of the challenges for scientists and educators alike is to come to grips with whether, when, and how spatial intelligence might serve as a common thread not only for education within a discipline but as a tool for developing broader ways of thinking.

My work has largely focused on the basic science of spatial learning and memory. By necessity, this work evolved from studying the general organizing principles of spatial memory and learning processes to investigating individual differences in a wide range of spatial skills. A large part of my focus is on how individuals differ not only in how well they learn, remember, and utilize spatial information but also in the styles, strategies, and profiles of spatial skills that they bring to bear on spatial problems. This area of work has naturally led to thinking about (1) how spatial skills develop (in childhood and through training), (2) how spatial skills interact, and (3) how different profiles of spatial skills might shape different types of learners. These questions have resulted in new lines of research that include spatial skill interventions for specific populations in college and in younger children. As such, the workshop has a direct relationship to current directions in my own research.

In addition to my research agenda, I have long been an advocate for educational outreach and have used my science as a tool for teaching high school students (and younger) about what it means to be a scientist, to ask questions, and to solve problems. In this capacity, I have become very interested in what it means to offer a STEM education and what evidence is still needed to make the case for stating that such an education will benefit individuals across a wide range of disciplines. To that end, I have begun working with a committee on K-12 STEM outreach at Johns Hopkins, and one of the fundamental questions we have been trying to answer is how to think about STEM as an approach that can be integrated into a curriculum. I would argue that spatial skills offer one of the clearest examples of a skill set that can be applied across many different fields, and this workshop is designed to essentially address this broader question at every level from the basic science to the implementation. With the current focus among educators, boards of education, funding institutions, and scientists on the importance of

STEM education, it seems that now is the time for this comprehensive approach to articulating the role of spatial intelligence in both the STEM fields and in bringing the principles of a STEM education to other academic and practical domains of knowledge. In addition, the workshop will foster the much needed cross-talk among the principal players at all levels from the scientists up to the educators and administrators who could implement evidence-based changes. I would be delighted to have the opportunity to participate in such a rich and timely discussion.

## Challenges to Integrating Spatial Thinking in the College Curriculum

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In considering this specialist meeting and the challenges we face in developing an action plan for potentially developing a spatial thinking curriculum, I have been thinking back on my last 6-years of research on spatial thinking in geosciences education. What has developed in this time is a clear sense of the reciprocal relationship between what cognitive science can offer geosciences education and what geosciences can offer cognitive science. Here, I reflect on three challenges this interdisciplinary work has presented to me a cognitive scientist because I think they may offer guidance on analogous opportunities (and threats) in developing a spatial thinking curriculum.

### ***Understanding how the mind thinks about space will be a foundation to build a spatial sciences curriculum***

Collaboration spanning disciplines that do not traditionally work together requires the collaborators be able to communicate with a clear understanding of the concepts and principles that are central to both disciplines—this is often characterized as developing a common language. This requirement is not just coming to understand each other's vocabulary – although this is not trivial and in our case it took at least a year to realize that in addition to learning each other's terms of art we needed to be clear on our usage of common terms, which we were using in subtly different ways. We needed to develop a framework for thinking about problems that encompasses both research areas. My geology colleagues refer to this as our "handshaking protocol." Our protocol, built on Chatterjee's 2008 typology, links the variety of spatial structures described by the scientist to the categories of spatial structures visualized by the mind (of novice and scientist). From the perspective of the academy a handshaking protocol based on spatial structures offers a common ground for the physical scientists who describes the complexities of spatial and spatiotemporal patterns in the natural world, and social scientists who describes the minds that seek to understand and use these patterns (as scientist of the world or just a person people who want to act in a coordinated manner in the world).

### ***Intellectual tools are needed to aid spatial scientists communicate and think about problems***

The struggle experienced by scientists of good will to communicate across disciplinary divides gave us an appreciation of the limitations of language. Communicating about spatial relations in particular is difficult with spoken language, which is limited in its ability to represent metric values. Geology, where metric spatial relations are central, has developed many terms of art to help experts communicate. The consequence for undergraduates learning geology is that they

are exposed to more new words in an introductory geology course than they would in an introductory foreign language course. To supplement the discipline specific terms Geologists notably employ gesture. A common anecdote is to hear someone at a conference observe, “Oh, see X there across the room, she is talking about her field area,” a deduction based on the hand gestures that accompanied the unheard conversation. Gestures allow geologists to communicate, and perhaps even to think about, complex spatial relations. We have found that Geologists employ gestures in each of the cells of Chatterjee’s typology, but that novices and experts gesture in different ways. We hope to abstract general principles of using gesture to communicate about spatial relations that could be used to help bring gestures into classrooms where spatial information is featured to provide students with a strong way to communicate about spatial information.

### ***Spatial thinking includes the body***

Although the geologists knew they gestured, and the psychologists knew the gestures were representing spatial relations, none of us had a clear framework to think about how people represent complex motions and shapes with human movement. How much information could be conveyed in gesture? Which aspects of motion mattered? This thinking led us to a recent effort to expand the interdisciplinary group to include dance choreography. Dancers are aware of how many different aspects of human motion can influence the viewer. We hope to use this explicit spatiotemporal awareness to help develop clear gesture-based instruction for scientific concepts that require understanding complex spatial changes. To understand how humans making meaning from the spatiotemporal patterns of human movement we have searched for the triple junction where fine arts meet the social and natural sciences.

## Spatial Thinking Across the College Curriculum

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Spatial thinking, at its very basic use of location or position, distance, directions, and movements, is fundamental for human activity and reasoning. Comprehending aspects of shape, size, orientation, and pattern underlies and enables our ability to read, write, and perform math. Yet the very constancy and pervasiveness of spatial thinking in our lives has led to its “background” status, overlooked by educators in all but a few situations. Explicit attention over the last decade has largely been from the STEM disciplines, as spatial thinking and STEM success are increasingly linked. We now know that some modes of spatial thinking (mental rotation, figure disembedding, etc.) can be taught and learned (see the recent Uttal et al. meta-analysis, and the work of Sheryl Sorby, among others), and this raises other questions and ideas. We still have much to learn about skill transfer, individual and group differences, and learning progressions. NSF-funded efforts like the Spatial Intelligence Learning Center are excellent first steps, and their linking to educational efforts, across all ages and levels, is critical. As is continuing their efforts at outreach and making bridges between research and practice.

Meanwhile, we find ourselves at a point where many academic and professional disciplines have taken a “spatial turn,” each defining and implementing their ideas about this in different ways. In the social sciences and humanities, place, space, and scale have become explanatory variables, or at least contributing factors worthy of consideration. “Place” is *de rigueur*. Maps as a universal form of information-rich representation are at a peak of popularity, in part for the new digital formats that leverage location-based services and our hand-held devices. This coincides with the humanities taking its own digital turn, and mapping-based projects are both common and central. We say that by merging narratives and numbers, we yield insights and offer novel ways of interpreting a story. What is not spatial within the arts? What expression of the fine arts, music, and theatre doesn’t have an individual realizing spatial relationships of their body and that of others, or the interpretation of notes arranged on a page? In the natural sciences, disciplinary approaches and bodies of knowledge are informed by our understanding of spatial processes, patterns, models, measurements, and systems. And we can look to remarkable growth of interest from professions such as business, law, and medicine, among many others. The end result is that the term “spatial” is popping up all over universities. Sometimes people on the same campus are even using GIS technology to ask similar questions about patterns, distributions, and relationships—albeit with very different objects or phenomena of interest—but their academic worlds exist in different realms and they don’t even know each other. Spatial analyses can be a marvelous common denominator, but only when we find ways to bridge our traditional silos.

And then there's geography, with its maps, spatial perspectives, and intrinsic attention to space, place, and scale. Has the interest in "spatial" spawned a growth in academic geography? No, not really. Some, in fact, strive to distance themselves from geography by calling their practices "neo-geography"—or by shunning the term altogether, perhaps in favor of "spatial sciences," as USC recently did.

Across higher education, this conflation of "spatial" and "geography" and "GIS" both confuses and bemuses. At best, the conflation either makes little difference, or might even drive some to stop and read when they otherwise wouldn't. Sometimes it is unintentionally propagated by an institution's marketing, public relations, and communications departments, whose staff are charged with describing Centers, publications, projects, and events about which they understand little. University Presidents have also been known to throw around the terms with reckless abandon. At worst, the conflation aggravates some academicians, misleads students, and undermines funding efforts, an audience for whom the differences truly matter. But in the end, it matters little what some call it. People have interesting ideas, with questions that involve location, position, place, or space, and they find approaches, methods, and tools designed to help them understand and answer those questions.

The University of Redlands is working to establish and nurture a "spatially-infused learning community." Our commitment to this is long-term, and we believe that the outcome will be dynamic, academically noteworthy, and worthwhile. Many people on campus *do* appreciate the differences between spatial, geography, and GIS, and that knowledge informs our research and practices. We are attempting to be systematic about this endeavor, and think through learning outcomes and assessment approaches that will accommodate the diverse ways in which different faculty, students, departments, and offices are engaging with the initiative. Like other "*Across the Campus*" initiatives, this one requires a thoughtful management plan for its care, implementation, direction, and maintenance. The broad administrative support we experience is in our favor, but that also drives expectations.

## Transforming Learning in Astro 101: Using Spatial Curricula to Teach Spatial Concepts

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Every year in the U.S., a quarter of a million college students take an Astro 101 course. 40% of all pre-service elementary and middle school teachers take such a course, with the majority indicating that Astro 101 stands as the last formal science course of their education. For many non-science majors, college level astronomy represents their last chance to learn about the body of scientific knowledge, the ways in which scientists model concepts, and the processes by which scientific knowledge is generated. Sadly, a large body of research indicates that these students will leave their Astro 101 course with little better understanding of the earth and universe than when they entered the course, indeed, with little better understanding than they had when they were in elementary school. This reality is troubling, considering that many of these same students go on to *teach* in elementary and middle school classrooms, where astronomy makes up a large part of standards-based instruction. It is therefore no exaggeration to state that an ineffectively taught Astro 101 course will likely result in poor primary school instruction. This gives us very good cause to find ways to improve our instructional practices at the college level.

The research work I share with my collaborators and our collective cadre of graduate students is largely concerned with the cognitive barriers that exist to students developing scientifically accurate conceptions in astronomy, and the ways in which our research findings can improve the effectiveness of our instruction. Given that instruction in the most reformed of classrooms results in students continuing to fail our domain's test of basic astronomical knowledge, we have little hope that the research lines of the past are going to help us. Instead, our work has turned to looking at difficult concepts to define the specific nature of the learning roadblock, whether that be some kind of phenomenological primitive, an issue of identity or belief, or most often in astronomy, a roadblock related to spatial thinking. Given our first wave of findings, we have begun developing inexpensive, easy-to-use curricula that support, or act in lieu of students' abilities to think spatially. While the majority of Astro 101 instructors would reject the idea of explicit spatial training in their courses, the idea of improving instruction with support for spatial thinking appears to be reasonably palatable. While we have no evidence that such Astro 101 instruction improves spatial thinking in a generalizable sense, data do suggest that these instructional interventions allow students to understand astronomical concepts that have eluded them for most of their formal education.

My comments here briefly describe our group's work in three parts:

- Establishing the underlying mechanism for the most robust misconceptions in astronomy,
- Developing curriculum that supports or replaces spatial reasoning for concepts in which spatial thinking forms the major barrier to learning,

- Crafting protocols for a systematic research agenda focused on the previous two tasks.

### **Moon phases, seasons, and the Big Bang; or "Why can't they learn this stuff?"**

Each of the science domains has at least a short list of misconceptions that appear to be unyielding in the face of typical instructional strategies, but in the field of astronomy and the space sciences, we think that we have more than our fair share. Even after a college level astronomy course, the average student cannot score better than a 50% on the TOAST (Test Of Astronomy STandards), an instrument constructed to assess learning of what is considered basic K-12 astronomy knowledge. Student understanding of the Big Bang, the structure of the universe, the causes of the seasons or of the moon phases, the Doppler shift, and the expansion of the cosmos does not occur, even in the face of constructivist and conceptual change teaching strategies. This failure in the educational process is well documented, although the cause of the failure is not.

Our initial investigations into the cause of our instructional failures has been influenced by the existing body of literature which indicates that, for some of these difficult ideas, maturity, educational opportunities, gender and culture are not important variables in influencing conceptual understanding. Rather, as we saw in *A Private Universe*, there is something about the human brain that simply does not like to think about the cause of Earth's seasons, for instance, in a scientifically accurate way, and that the preferred manner of thinking varies little between an 14-year-old, middle class girl with an 8th grade education, and a fifty-something, upper middle class, PhD-bearing full professor at the world's most prestigious institution of higher learning. We find this equity, across so many important education variables, to be nothing short of shocking, and a clear signal that if we are to craft improvements in instruction, we have to start thinking about the influence of cognitive structures. Moreover, we must do so at the level of the specific astronomical concept.

We assert that there are perhaps four primary barriers to learning astronomy, that are completely unrelated to traditional predictors of educational achievement (e.g.: access to good schools, socioeconomic status), and that spatial thinking is the greatest of these barriers to understanding astronomical concepts. However, we believe that spatial thinking is important for some aspects of astronomy and not for others, and that the impact of spatial thinking to learning cannot be deduced simply by reviewing the surface features of the task, or by performing a traditional rational task analysis. Our first forays into determining the role of spatial thinking in Astro 101 indicates that in some cases, those concepts that appear to rely on spatial thinking, such as the structure of the universe or that cause of day and night, do in fact rely on spatial thinking. In other cases, such as the case of the Big Bang, spatial thinking seems to have little impact on learning, even though the concept is the ultimate example of the expansion of matter and space. In recent work looking across the breadth of the Astro 101 domain, we observed that overall astronomy knowledge and students' knowledge gains, are correlated to some measures of spatial thinking, but they are not highly correlated with students' course grades, majors, or general academic success, and that the correlations for individual concepts vary widely.



Considered collectively, the work we have done thus far represents the bulk of research into spatial reasoning in college level astronomy, and that work is very nascent. We are currently taking on this problem in rather broad swipes, but the work is promising, and is already resulting in a few very effective instructional interventions for the Astro 101 classroom.

### **Changing the Way We Teach Astro 101**

Having some indication of the places in which spatial thinking influences learning of astronomy concepts, we've turned part of our attention to developing or adopting pragmatic instructional strategies that support the student as they attempt thought processes that rely on spatial abilities. In our reiterative research model, we empirically examine the interventions in light of their potential to move students toward scientifically accurate and generative conceptions. With regard to astronomical geography, orbit-related, and tilt-related phenomenon, the data suggest that a curriculum that supports, or acts in lieu of a student's spatial thinking, can transform their understanding of the content, in a very short amount of time, and in conditions in which traditional and reformed teaching practices have already failed. Early data indicate that this is also true for a newly developed curriculum related to the structure of the solar system. In both cases these interventions have been successful with a variety of students, including those who are underrepresented and those who were considered "at-risk" of failing to do well in the course (e.g.: second language learners). This work indicates that some of the more robust misconceptions in Astro 101 can be overcome by matching instruction to the specific cognitive barriers that block student understanding, including the barrier of spatial thinking.

### **A Systematic Approach to Understanding Spatial Thinking in Astro 101.**

Our intention is to tease out the role of spatial reasoning in Astro 101, one concept at a time. We are now in the process of investigating those ideas that we know to be recalcitrant in the face of all currently used methods of instruction: issues largely related to the celestial sphere, and to astronomy's unique sense of time and scale. For the majority of these concepts, we hold the existing assessments somewhat suspect, necessitating the construction of new instruments that validly measure student understanding, but which are not biased by working memory or verbal ability. For each concept we are attempting to determine the specific nature of the spatial reasoning difficulty, (e.g., visualization, transformation, environmental reasoning) in order to tightly tailor instruction.

My goal in attending the specialist meeting is two-fold. First, I am hopeful that I might gain insight in to the frameworks and instruments being used in other disciplines so that we might parallel that work to the extent possible. Such commonalities should naturally facilitate communication and cross-disciplinary comparisons. Second, I hope to discover pathways that promote communication and collaboration between the discipline-based researchers in the sciences, and the spatial thinking researchers within the human sciences.

## Spatial Skills Training to Improve Student Success in Engineering

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Engineering has long been known to be among the most spatially demanding professions. In studies conducted by the Johnson Research Foundation, the spatial skills of more than 60,000 professionals were examined and it was found that engineers have the highest level of spatial ability compared to all other occupations in the study. In fact, the spatial skills of engineers were even higher than those of architects. Spatial skills are part of the national standards in K-12 mathematics education<sup>2</sup>, yet problems in spatial cognition are rarely included on high stakes tests at the state level and thus are infrequently included in K-12 mathematics instruction. There are many background factors thought to help students improve their spatial skills<sup>3-5</sup>, including playing 3-D computer games, playing with construction toys such as Legos, or enrolling in shop or drawing courses; however, many children, particularly women and minorities, often do not participate in these activities. The result is that there is a large number of students who enroll in university studies who never had the opportunity to develop their spatial skills and are at a disadvantage in spatially demanding fields such as engineering. Engineering has been struggling as a discipline for decades to diversify the profession; improving spatial skills of women and minorities could be a key to helping us along this path. Table 1 includes select data gathered by the author since 1996 regarding scores on the PSVT:R earned by enrolling engineering students<sup>6</sup>. For the data presented in this table, significant gender differences exist for all groups; differences between white and African American students of both genders are significant, as are differences between White males and American Indian males.

**Table 1.** PSVT:R Scores Disaggregated by Gender/Ethnicity (max score=30)

	Male		Female	
	n	Average (Std dev)	n	Average (Std dev)
<b>African American</b>	81	19.284 (5.788)	36	14.000 (5.575)
<b>American Indian</b>	58	22.828 (4.784)	14	20.571 (4.090)
<b>White</b>	6347	24.443 (3.978)	1155	20.602 (4.802)

Based on these factors, the author has been involved in the development and implementation of a course and curriculum designed to improve spatial skills among engineering students for nearly two decades<sup>7</sup>. The current form of the training program consists of a 1-credit course that meets once per week; however, in recent years, the spatial skills curriculum has been adopted by a number of engineering colleges across the country and delivery methods have varied somewhat from this model. The materials used in the course consist of a workbook and

multimedia software developed by Sorby and Wysocki with funding from the National Science Foundation<sup>8-9</sup>. The engineering students take the Purdue Spatial Visualization Test: Rotations<sup>10</sup>, a test designed to assess mental rotation ability, and those who fail the test with a score of 60% or less are targeted for spatial skills training. In 1993, the initial year that the spatial skills course was offered, students failing the test were randomly selected for participation in the training course; between 1994 and 2008, students who failed the test self-selected into the training course; and, from 2009 through today, students failing the test are required to participate in the training course.

From longitudinal data collected through the years, there is strong evidence to suggest that spatial skills training has had a significant positive impact on student success, particularly for women engineering students<sup>11</sup>. [In this analysis student success is measured by course grades and by retention/graduation.] Table 2 includes average course grades earned by students from three groups: **1)** those who marginally passed the PSVT:R with a score of 60–70%, **2)** those who failed the PSVT:R and did not enroll in the spatial skills course, and **3)** those who failed the PSVT:R and did enroll in the spatial skills course. From the data presented in Table 2, there is strong evidence to suggest that spatial skills training has a positive impact on grades earned in several introductory STEM courses. Through participation in the spatial skills course, students with initially weak spatial skills outperformed not only those who initially had similar spatial skills scores, but they also outperformed students whose spatial skills were slightly better.

**Table 2.** Average Grades Earned by Students by Initial Spatial Skills Test Scores

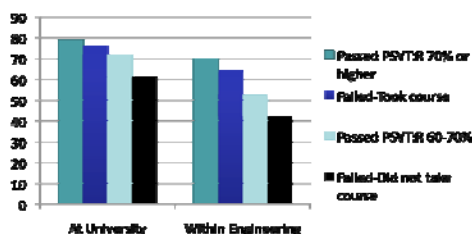
	<b>Marginally Passed PSVT:R</b>	<b>Failed, Did not enroll</b>	<b>Failed, enrolled</b>
<b>Pre-Calculus</b>	2.42 p = 0.003 (s=1.149, n=247)	2.19 p < 0.0001 (s=1.263, n=155)	2.75 (s=1.105, n=147)
<b>Calculus I</b>	2.48 N.S. (s=1.204, n=391)	2.25 p = 0.005 (s=1.327, n=217)	2.59 (s=1.276, n=188)
<b>Chemistry I</b>	2.47 p = 0.024 (s=1.048, n=456)	2.31 p = 0.0005 (s=1.144, n=266)	2.64 (s=0.975, n=216)
<b>Intro Computer Science</b>	2.88 p = 0.027 (s=1.132, n=149)	2.53 p < 0.0001 (s=1.129, n=101)	3.16 (s=0.806, n=74)
<b>Overall GPA</b>	2.84 p = 0.0005 (s=0.705, n=530)	2.63 p < 0.0001 (s=0.808, n=305)	3.01 (s=0.529, n=234)

In fact, similar trends are found when students are required to take the spatial skills course and self-selection is not a factor. Table 3 includes data comparing student performance between those who initially failed the PSVT:R and were required to enroll in the spatial skills course with those who marginally passed the PSVT:R with a score of 60–70%<sup>11</sup>. Although not all of the differences in average grades are statistically significant, the trends towards improved grades through spatial skills training are evident.

**Table 3.** Average Grades Earned by Students by Initial Spatial Skills Test Scores

	Marginally Passed PSVT:R	Failed Test, Enrolled in Course	Significance of Difference in Grades
Pre-Calculus	2.06 (s=1.093, n=62)	2.23 (s=1.161, n=61)	N.S.
Calculus I	2.27 (s=1.384, n=120)	2.63 (s=1.323, n=106)	p = 0.024
Chemistry I	2.35 (s=1.061, n=149)	2.51 (s=0.946, n=129)	p = 0.096
Computer Science I	2.25 (s=1.356, n= 20)	2.63 (s=1.008, n=16)	N.S.
Overall GPA	2.64 (s=0.907, n= 199)	2.83 (s=0.726, n=187)	p = 0.012

Not only does the spatial skills training appear to have a significant positive impact on grades earned, but there is strong evidence to suggest that the training has also had a positive impact on student retention/graduation rates. Figure 1 shows the graduation rates for students who began their studies in the 1996-98 timeframe broken down by initial spatial skills test score<sup>11</sup>.



**Figure 1.** Graduation Rates from the University and Within Engineering

For the data presented in Figure 1, there is no statistical difference in graduation rates between students who initially scored higher than 70% on the PSVT:R and those who initially failed the PSVT:R who went through the spatial skills training; however, there are significant differences between the group who initially scored 70% or higher and those who marginally passed as well as those who initially failed the PSVT:R who did not enroll in the spatial skills course.

**Conclusions**

From the data gathered by the author over nearly two decades, it is apparent that there is a link between well-developed spatial skills and success in STEM fields. This link is especially apparent when examining graduation rates comparing students who initially scored above 70%, those who scored 60–70%, and those scoring below 60% who did not participate in spatial skills training. For these three groups of students, those who scored above 70% had statistically higher graduation rates than the other two groups. Furthermore, providing students with the opportunity for spatial skills training improves graduation rates for the group initially failing to be on par with those who started out their university studies with strong spatial skills. With the national and state-level focus on improving graduation rates in STEM fields, it appears that spatial skills training could play a critical role in enhancing student success, particularly for women and underrepresented minorities.

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## Spatial Thinking Across the College Curriculum

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Spatial thinking is a fundamental component of learning and problem solving in the college curriculum, specifically in the STEM disciplines. From their first courses in physics, mathematics, chemistry, and geology, students are tasked with developing mental models that include information about spatial relationships among components in a physical system. For example, students must learn to recognize important structural features in molecular compounds and geological formations in freshman courses. As students progress through STEM courses, they must learn to reason about increasingly complex spatial systems and how spatial relationships change dynamically over time. For example, physics students must learn to calculate changes in force and momentum based on the spatial trajectory of colliding objects and biology students must learn to identify how electrostatic interactions between amino acids cause proteins to fold into highly ordered structures. It is clear that the study of spatial information and dynamic spatial relations are central to all STEM disciplines.

As a professor of chemistry, I can speak firsthand about the role of spatial thinking at all levels of instruction in the chemistry. A typical, ACS-approved baccalaureate degree in chemistry requires students to complete courses in General Chemistry, Organic Chemistry, Inorganic Chemistry, Analytical Chemistry, Biochemistry, and Physical Chemistry. In each of these courses, students must learn to recognize important spatial relationships within and between compounds. While early instruction involves the identification of common molecular shapes and geometries, more advanced instruction requires students to predict the movement of electrons and atoms as they rearrange in complex multi-step reactions to produce new compounds with distinct structural features. Ultimately, students face significant difficulties in the final courses of the major as they are tasked with identifying symmetry elements (e.g., mirror planes, rotational axes, etc.) in complex molecules and analyzing spectroscopic data to predict the three-dimensional structure of unknown compounds synthesized in the laboratory. Arguably, chemistry is the “most spatial” of all the STEM disciplines.

It is important to note that in chemistry as in all STEM disciplines, spatial thinking involves multiple cognitive processes and mental representations. Perhaps most well known among these is imagistic reasoning or “visualization,” a cognitive process by which students are believed to generate and inspect internal representations that include visual images of spatial information. However, spatial thinking involves the generation and manipulation of internal representations other than analog mental images; spatial thinking also involves reasoning via motor schema and abstract spatial representations. Moreover, spatial thinking does not exclusively rely on internal mental representations, but involves the careful construction, interpretation, and modification of external representations, such as diagrams as well as physical

and virtual models. In sum, spatial thinking in STEM involves a complex interaction between multiple processes and representations that creates many challenges for college students as they pursue a STEM degree.

Although spatial thinking is clearly ubiquitous in college STEM courses, my own research indicates that spatial thinking (of all kinds) in chemistry and other STEM disciplines is *task-specific*. That is, throughout a given disciplinary curriculum, student achievement is not solely determined using assessments that directly require reasoning about spatial relationships relevant to the domain. In fact, many assessment items evaluate students on their ability to reproduce declarative knowledge, to interpret and construct disciplinary representations, and to analyze experimental data. To complete such tasks, spatial thinking is not relevant to produce a reasonable problem solution. Given this, outstanding questions remain regarding when spatial thinking is required to understand STEM concepts and how spatial thinking contributes to STEM problem solving.

To that end, much research has been devoted to understanding the causal factors responsible for the challenges STEM students face when engaged with spatial thinking. Although much of this work has demonstrated a relationship between students' spatial abilities (i.e., mental rotation and spatial visualization), it is my opinion that individual differences in spatial ability only partially account for the success and failure of many students to succeed in STEM. As above, spatial thinking requires more than the simple application of spatial ability to problem solve successfully: even students with high spatial ability struggle in STEM courses at all levels. In my own research, my collaborators and I have shown that both high and low spatial students experience challenges learning to interpret formalisms of disciplinary representations and to apply heuristics to scientific diagrams. Thus, individual differences in spatial ability do not fully explain the variance in student achievement or STEM degree attainment.

Indeed, STEM achievement for high and low spatial ability students can be significantly improved by novel instructional practices. Among these practices are "spatial interventions" that help train students to engage in spatial thinking in the STEM classroom. Importantly, in my own work, my collaborators and I have studied the impact of organic chemistry interventions that not only train students to apply strategies that involve mental imagery, but also interventions that help students learn to apply analytic strategies to decode spatial information in diagrams using disciplinary algorithms. This work has shown that individual differences in spatial ability are less predictive of chemistry achievement than students' ability to apply trained problem solving strategies. Perhaps more interesting, we have observed that the best achievement among all students, and women in particular, results from interventions that train the synergistic application of disciplinary algorithms and mental imagery when engaged in spatial thinking.

It is clear that spatial thinking in chemistry and other STEM disciplines plays a central role in the college curriculum. Only recently has this role been fully appreciated by STEM researchers and STEM educators, and further research is needed to understand the challenges students face engaging in spatial thinking in general and in each STEM discipline. Importantly, additional research is needed to study the impact of new interventions that aim to improve students'

spatial abilities as well as those interventions that aim to improve representational competence or flexible strategy choice. It is critical that the community of educators recognize the central role of spatial thinking in STEM teaching and learning; however, they must refrain from limiting access to STEM programs to only those students who excel on spatial ability measures. More work is needed to understand how best to support students who all ability levels to succeed in STEM courses.



# Spatial Thinking Across the College Curriculum

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Stanford University is in the position not unlike many others across the United States in that it lacks a Geography Department. This absence has created both opportunities and challenges for those teaching spatial thinking and concepts to both undergraduate and graduate students. The most relevant opportunity is to include the ability to integrate spatial concepts directly into subject-specific classes making the examples and the work more relevant to the learner. Challenges emerge when there is a lack of coordination as to what should be taught to all students, the desire of students to jump into their research rather than to understand the theory, and the concern that spatial thinking is only presented to the students when the faculty thinks it relevant to do so.

It is clear from working with students in the map collections that most have little background in reading maps, much less understanding them as carriers of distilled information conveying a specific point of view. More so than with textual information, students seem to believe that what is presented on a map is factual and do not think to question it as they would with text. The same has been observed when they encounter geospatial data. Little has prepared them to understand the nature of the data with which they work. Students come to spatial data with scant knowledge of scale, projection, map reading, or spatial analysis skills. Without a systematic training program, the students pick up this knowledge in a haphazard, unstructured way, either on their own or through disparate teaching.

Stanford University presents an environment with entrenched silos of expertise. The culture encourages this even in the midst of a strong push towards interdisciplinary research. It is a culture of innovation and entrepreneurship that fosters independent thinking and the desire to quickly move into new areas of research. Over the past dozen years the campus has strongly embraced geospatial research and thinking in the curriculum. The sciences were the first to move in this direction followed by the social scientists and then the humanists. The classes offered throughout the university mirror this diversity.

- Civil and Environmental Engineering—Environmental and Water Resources Engineering Design
- Electrical Engineering: The Earth from Space—Introduction to Remote Sensing
- Geological and Environmental Sciences: Geostatistics for Spatial Phenomena
- Geophysics: Remote Sensing of the Oceans
- Political Science: Spatial Approaches to Social Science
- Anthropology: Cities in Comparative Perspective
- History: Spatial History—Concepts, Methods, Problems
- Classics: Modern Journeys in Ancient Lands—Building a Spatial History of the Grand Tour

While the classes all integrate aspects of spatial in their mix, they tend to focus on applied teaching rather than on understanding basic spatial concepts and analysis. The class “Fundamentals of Geographic Information Systems” taught by Patricia Carbajales, the library’s Geospatial Manager, counters this approach. The four unit class is the only one taught in the university (once a year) that provides a solid foundation in the principles of cartography, geographic data structures, statistical analysis of geographic data, spatial analysis, map design and GIS software. Students from across the schools take the course; it is required for urban studies students. While not required for students in Civil and Environmental Engineering, Earth Sciences, Political Science or History, many take it knowing they will need this background to do their work.

Branner Earth Sciences Library provides the backbone of support for geospatial data, teaching and software across the campus ([lib.stanford.edu/gis](http://lib.stanford.edu/gis)). The program, run by Patricia in conjunction with 30 hours of assistant support a week, supports over 600 users on the campus. We offer numerous workshops on a regular basis including Introduction to ArcGIS; GIS Data Creation & Management; Basic Spatial Analysis; Google Earth, Maps & Fusion Tables; Spatial Statistics; and ArcGIS Online, Business Analyst & Community Analyst. After taking the Introduction to ArcGIS workshop (3 hours), the students may book individual appointments for reference help.

Clear trends have emerged over time as we have worked with hundreds of students and researchers. First, it is hard to persuade students as to the importance of taking time to learn and understand the fundamental concepts of spatial thinking that underpins GIS. They want a rapid turnaround for their time and are under pressure to do things quickly. This is combined with software that is getting easier to use and more accessible to a novice user. One may be able to click a button and get results, but without proper training one cannot critically analyze the results. It takes time to learn about datums, projections, coordinate systems, data management, and the difference between raster and vector models, the concept of scale and its effect on the structure of the data, classification methods, and the importance of solid metadata. It is a challenge to work with faculty to enforce these training concepts when they themselves have not been trained to think spatially. It makes it difficult for them to know what to ask for and, at times, expect things to be easier or faster to do.

What can the library do to help fill the gaps in the teaching curriculum? First we are in the final stages of hiring a dedicated GIS Instruction and Reference Specialist. This position will oversee the introductory workshop program that is required of all students and researchers who ask for support for our unit. This basic, introductory workshop has proven indispensable in equipping our students with their first exposure to the fundamentals of GIS and also to the software tools available in our lab. The person will also manage the support staff, often students from the San Jose State University Geography Department, who handle the bulk of the general reference interactions. This will give us 70 hours of dedicated support in addition to the Geospatial Manager.

Second, we are also starting to build out a highly specific training program structured around different disciplines. Patricia piloted this program over the summer in conjunction with faculty in Political Science and in History. One set of classes took place over the course of a week and the other stretched over a few months. Our goal is to work with faculty to create robust, relevant training specifically geared to their students that become required training when working with spatial data and spatial concepts. Questions remain as to the ability to scale such an operation or the willingness of the faculty in diverse disciplines to work with us to develop relevant training materials. So far, the response has been overwhelmingly positive.

Finally, the centralization of geospatial support in Branner Library has, in some ways, been a boon given the distributed, siloed nature of the campus. It allows us to create a suite of services that are distributed in a consistent way with a well-thought out strategy for support. We centralize the training of assistants giving us the ability to know that outreach will be competent, thorough, and relevant to student and researcher needs. It is clear we are providing a necessary piece of the puzzle for those working to integrate spatial thinking into their teaching and research.

# A Design Perspective on Spatial Thinking for Spatial Thinking Across the College Curriculum

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In a recent *NY Times* op-ed piece, architect Michael Graves (2012) wrote, “Drawings are not just end products: they are part of the thought process of architectural design. Drawings express the interaction of our minds, eyes and hands.” That interaction between the minds and hands is an expression of the commonly held belief in undergraduate design education that drawing and designing are fundamental to developing spatial thinking. Whether studying 2-dimensional representations or working to better understand 3-dimensional space, architecture and landscape architecture students spend a tremendous percentage of their time in college improving their spatial cognitive skills. As accredited degree programs, design curricula are often structured around a larger credit load and higher faculty contact time, and even higher time commitment for student work compared to other undergraduate curricular approaches.

At the heart of design education is the design studio. This is an intense problem-based learning environment (Tulloch and Graff 2007), known on many campuses for its late nights and long weekends of work. Bearing in mind the underlying fundamentals of spatial thinking behind even basic design exercises, design studios require students to rapidly advance their spatial skills through an immersion in the studio environment. Aside from the rapid immersion and problem development, this environment is also characterized by the applied problems that constitute the core of most studio instruction and result in formative approaches to spatial problems requiring interventions. Because of the learning curve and broad knowledge required, about half of the undergraduate LA programs in the US are offered as 5 year degrees, adding greater depth to the immersion experience. In the same way that geometry and geography are clearly different, but both inform spatial cognition, spatial design, particularly landscape architecture, has a very large portfolio of unique experiences and lessons that should be integrated into any serious study of spatial thinking in higher education.

## Sensory learning

In studio settings, some commonly used preliminary exercises with this impact include: freehand drawing of forms, freehand drawing of negative space, rapid construction of small-scale models, rapid construction of large-scale models, measured drawings and field work. The effect is that, collectively, these lessons create a deep awareness of space and spatial relationships for many of the students, and they do it through a wide variety of sensory connections. Many of these exercises might only work in fairly specific settings, but they represent a large realm of educational experiences that warrant fuller exploration for spatial education.

Drawing exercises and courses represent a large category of these sensory exercises. Freehand drawing places an emphasis on creative viewing of our personal environments. As students explore edges and surfaces, they often engage in a freehand technique called contour drawing (decidedly different than contour mapping). To better develop a sense of space, they will also draw the “negative space” between complex, overlapping objects.

Measured drawings (i.e., mechanical drafting) might begin with traditional blocky forms, reduced to 2-d or represented in 3-d axonometric representations. Cross-sections and elevations are also among basic spatially-oriented drawing exercises. For a deeper experiential memory, some classes use early exercises of measuring and drawing existing landscape features based on field measurements. This might mean a detailed cross-section of a city street, capturing each change in material and surface. Or it might be a full-day effort to construct a measured quadrat drawing of a single tree. Taking these experiences a step further is the development of built scale models of both built spaces and natural landscape forms. While some of these skills are formally taught, many are simply learned through frantic immersion into a project with specific needs.

Perhaps more than other design fields, landscape architecture relies heavily on the field trip as a spatial education experience. Our program uses annual 4-day program-wide trips to pack our students’ sensory memory bank with experiences linked with spatial lessons. When visiting the FDR Memorial in Washington DC the muffled or reflected sounds of planes leaving Ronald Reagan National Airport create multiple opportunities in space and distance. The amazingly long, but relatively narrow, reflecting pool at Boston’s Christian Science Plaza allows students to compare plans with experience, to pace off a large object in the field. Students (and eventually professionals) find these memories of spaces to be tantalizingly vivid years later when they need to imagine a parallel space or experience or distance.

### **Design studio**

The design studio is one of the most identifiable icons of design education. These are commonly treated as required core classes for anywhere between 5 and 10 consecutive semesters, with one class sometimes being 6 credits for 12 contact hours over three days a week. While the formats vary somewhat, they often revolve around studio classrooms spaces that are accessible 24/7. For many, the entire semester might build on a single extended design project, employing methods sometimes described as problem-based learning, to address a spatially-explicit problem. With relatively limited introductory instruction in map-reading, students are quickly immersed in the process of using, drawing, and imagining space and form in ways that will take years to master.

Studio’s high contact time is meant to allow one-on-one interactions between faculty and students (desk crits). Since students are often asked to quickly display their current unfiltered spatial abilities, instructors can address some shortcomings individually rather than with the entire class. It is a much less rules-based and more needs-based approach to spatial learning, with clear shortcomings and benefits.

One of the most notable differences between design studios and lecture classes are the decisions that students make throughout the class. Confronted with an assigned problem, they

acquire knowledge of the site and the problem, develop alternative solutions to address the problem, and ultimately chose and refine a preferred solution. Since these are spatial problems, the exploration is also spatial. On large projects they may use GIS to develop inventory and analysis materials, but on smaller sites designers may rely more on personal observation and sketching. Landscape architects synthesize these complex spatial patterns and information (whether digitally or mentally or both) to inform their decisions. And those decisions, or designs, often require iterative development of alternatives. After 6 semesters of this, students have accomplished an impressive amount of spatial learning and yet find themselves far from the level at which practitioners often operate.

### **Evaluating spatial thinking talent versus skill**

With such specialized facilities and specific accreditation requirements, a number of the undergraduate design programs employ either a program-specific admission process (often in the guise of other names like “limiting enrollment”). The approaches vary widely. One architecture program offers a 1-day “exam” which tests both spatial thinking and creativity with unusual drawing exercises and construction paper puzzles which are then blind-reviewed by faculty. A student untrained in drawing may struggle with some exercises, but shine on others. At the same institution, the landscape architecture program relies mostly standardized test materials that test both visual and spatial acuity. Still others require a semester or more of instruction at their institution, which not only tests their spatial abilities but also tests their ability to learn spatial thinking.

These processes are based on a key set assumptions that are relatively untested. Are spatial cognitive skills inherent and testable without preparation? Are they universally learnable? Decades of design instruction have led a number of design programs to believe that, in some cases, spatial perception and thinking is demonstrable in a way that should change the course of students’ academic careers.

### **Overlap between geography and design**

It is not news that landscape architecture and geography overlap. But, reflecting on that overlap may highlight new areas of investigation. For instance, there has been a growing area at the intersection of these and other fields called geodesign. As geodesign has emerged (with a 4th annual meeting planned for January 2013), it has explored the shared territory and the key differences. An interesting divergence that came up at one of these meetings was that the two fields describe different scales using the same words but with opposite meanings.

An historic example of this shared experience is the spatial software innovation hub that was the Harvard Computer Graphics Lab from the mid-1960s to the early 1980s. This lab, housed in Harvard’s Graduate School of Design, benefitted from the depth of spatial theory in geography and the creative approach and goal-based needs of planners and designers in creating some of the most important spatial software in the world.

**Spatial education lessons and questions (as if they are different)**

These different approaches from landscape architecture all highlight a significant value in active learning. The self-guided explorations, coupled with tactile experiences, potentially lead to much deeper memories of the specific spatial lessons. And yet, the design approach is time consuming and difficult to justify in other curricula. While a well-trained geographer and landscape architect both have clearly demonstrable spatial abilities that have been learned, it remains unclear how similar their understandings of space and scale and dimensionality are or whether (as a group) they have similar abilities to analyze and synthesize spatial information in similar ways. Still, there may not be a more rapidly applied or more deeply-based immersion approach to spatial education, than what we see in studio.

We still don't know much about these approaches to learning spatially. From the time they commit to design, landscape architecture students have committed to interventions and what Graves calls "formative actions" while non-design disciplines start with more open inquiries and explorations. Does a focus on decisions and interventions alter a student's perspective on space? Do the realities of professional practice impose an urgency that forces clarity or carry a burden that limits critical spatial thinking? Ultimately, do the less literal exercises add or detract from spatial education?

Finally, there is merit in asking whether all students (or at least a substantial subset) should be required to complete a first-year class in spatial awareness. But an examination of design adds the possibility that some groups of geographers/cartographers might progress more rapidly after beginning with a drawing class or immersive design studio.

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# Spatial Thinking

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**S**patial thinking is not unitary but rather a complex of skills that not only can be cultivated but must be. Spatial thinking is key not only to professional life but also to everyday life, to understanding and using the multitude of maps, graphs, sketches, diagrams, and spatial descriptions, concrete and abstract, needed to carry on the business of life. Despite difficulties that children and adults have in aspects of spatial thinking, it is rarely taught.

Spatial thinking in various instantiations has occupied my research for years: objects, bodies, the space around the body, the space of navigation, the spaces people create to augment their own cognition and well-being. Putting ideas on paper, in sand, on stone, are ancient means for remembering, conveying, and manipulating ideas, concrete, like maps, and abstract, like mandalas and diagrams. We have studied the natural mappings people construct using place in space, horizontal, central, vertical, and simple marks in space, like dots, lines, arrows, blobs and configurations of them to represent structures, such as maps, buildings, and networks, as well as processes, such as explanations of how to do something or how something works. We have also studied how people interpret and understand visual expressions of thought and related diagram production and use to spatial abilities. Those high in mental rotation, for example, not only produced better diagrams for explaining processes but also more effective language for explaining processes (e. g., Daniel and Tversky, 2012). By contrast, those adept at finding embedded figures were better at finding new interpretations in ambiguous sketches, a component of creative thinking (e. g., Tversky and Suwa, 2009).

What if there is no paper? People draw in the air, that is, gesture. Like diagrams, gestures spatialize both concrete and abstract structures and processes using virtual marks in a created space. In two sets of studies, students, alone in a room, read descriptions of spatial problems and attempt to solve them (Kessell and Tversky, 2006; Jamalian, Giardino, and Tversky, 2012). Many of the students gesture while reading the problems and their gestures structure the spatial situation described. Those who gesture are more successful at solving the problems. Gestures can be incorporated into computer modules for teaching. Children's performance in mathematics was enhanced when the gesture actions were congruent with the thought actions (Segal, Tversky, and Black, submitted). In particular, addition was better with discrete gestures and number line estimation was better with continuous gestures.

Viewed gestures can also facilitate student learning if the gestures correspond to thought. Kang, Tversky, and Black (2012) used the same diagram and verbal script to teach the workings of an engine. Half the students saw gestures showing structure, half saw gestures showing action. Structure is usually easier to grasp than action, and both groups did well. The group who had



viewed action gestures performed better on action questions and conveyed more action information in their subsequent visual and verbal explanations, inventing their own gestures to do so. Jamalain and Tversky (2012) found that viewed gestures changed the ways people thought about time, specifically, understanding cyclicity, simultaneity, and temporal perspective.

Encouraging spatial thinking is easy to adopt in classrooms and has immediate benefits on student learning. Bobek and I (in preparation) taught junior high students lessons in chemical bonding and mechanical thinking. They were first tested, and then asked to construct either a visual or a verbal explanation of the processes, followed by a second test. All students improved on the second test without intervening teaching. Those who constructed visual explanations improved far more. In our view, the visual explanations were superior because they can map the processes to space. Diagrams provide a check for completeness, a check for coherence, and a platform for making inferences from structure to process. They also provide useful feedback for teachers.

Children (and adults) need to learn structure and process in many domains, STEM, history, literature, and more. Spatializing thought through diagram and gesture can be easily incorporated into the classroom, with clear benefits.

## Envisioning the Spatial Curriculum: A Research Agenda

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I am excited about this conference and the possibility of attending. My research interests focus on the malleability of spatial skills and the role of maps and other representations in spatial thinking. Thus I think I would both contribute to and benefit from the conference. I've organized my application around two themes: My perception of the value of a spatially-oriented curriculum, and a foundational research question that I think must be explored as we embark on developing these spatially-oriented curricula.

### *The Value of a Spatially-Oriented Curriculum.*

A spatially-oriented curriculum is one that stresses the need to think about relations among facts or locations. Students are confronted with great masses of information, covered in ever-expanding textbooks that now approach 1000 pages in length. Representing and thinking about information spatially can help students to see relations and patterns among facts, rather than simply memorizing burgeoning lists of them. With Bob Kolvoord, I am investigating how working with GIS promotes thinking about new science and engineering problems in spatial ways. At the conference, I would discuss the possibility that infusing GIS-based instruction into early science and engineering classes could promote spatial thinking across the STEM curriculum

More specifically, I think that a spatially-oriented curriculum would allow students to transfer information and approaches to problem solving. Transfer of abstract ideas from one topic to another can be notoriously difficult, and consequently, students learn bodies of information in one class that have little, if any, connection to what they have learned before or what they will learn next. Bransford & Schwartz, 1999 argue that effective transfer often involves learning *how* to think about information in consistent ways, despite changes in the specific topics. Spatial representations may provide a foundation for transfer of information because they provide a common framework for approaching different kinds of problems and thus help to reduce the tendency to treat each course as a separate silo.

**Research Question.** To implement effective spatially-oriented curricula, we need careful and specific research on several important questions. Here I discuss one set of question that I think could be one potential topic for the conference.

*Spatial Practices and Spatial Abilities.* There is no doubt that cognitive ability profiles greatly influence who goes into STEM fields (e.g., Wai, Lubinski, & Benbow, 2009). However, we need to be careful about assuming that these ability profiles necessarily reflect what scientists actually do. As I have argued elsewhere (Uttal & Cohen, 2012), spatial abilities may be particularly

important early in learning, but their importance may actually decrease as students learn more and become experts. Science education will often involve the acquisition of a large number of distinct *practices*—methods and approaches for solving problems. This point is stressed in the most recent National Research Council (NRC) guidelines (2012) for science learning, which suggest that we should define scientific thinking more in terms of what scientists *do*, rather than in terms of either cognitive abilities or specific bodies of knowledge. Scientific practices will often involve spatial thinking, but this “thinking in practice” will not be easily characterized or captured by solely by spatial ability tests. For example, the acquisition of a spatial practice may involve learning different ways to represent information via computer, or when and how to sketch in different ways.

At the conference, I would like to discuss research on the relation between spatial abilities and the learning and development of spatial practices. This relation may not necessarily be simple and direct. For example, it seems possible, even likely, that students who approach mental rotation problems using strategies instead of holistic processing may end up preferring to solve a host of problems in different ways (e.g., Khozhenikov, Kossly, & Shepard, 2005). To me, this is fundamentally a question of development; we are interested not only in the cognitive abilities that predict STEM achievement and attainment, but also in how these abilities influence choice and preferences, and, ultimately, patterns and practices of problem solving.

These questions are not easily answered in the course of a typical psychology experiment or even an academic year. They will require longitudinal studies, perhaps beginning in high school and following students for a year or more into college. These studies are challenging but not impossible, and I think one potential outcome of the conference in Santa Barbara would be the initial development of plans for large-scale studies. Bringing together spatial cognition researchers and natural science educators provides an opportunity to think systematically about the kinds of research that needs to be done. Moreover, it could engender a community that uses similar measure and thus supports the pooling of data across different institutions. I very much look forward to participating in this effort.

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## Cultivating Spatial Intelligence

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My everyday work and thoughts on the topic of this specialist meeting are guided by three fundamental arguments (or truths as I like to think of them). The first is the notion that spatial is cross-cutting and that the work of many scholars in the sciences, social sciences and the humanities as well as the professional schools would benefit from various forms of spatial analysis, modeling and visualization. This is, of course, partly borne out by the spatial turn that has swept across these fields in recent decades (e.g., Casey 1997, Gieryn 2000, Ethington 2007, Scholten et al. 2009, Newcombe 2010).

The second is the notion that fundamental advances in geographic information science drive technological innovation (i.e., the development and distribution of open source and proprietary tools), that these cutting-edge geospatial technologies, in turn, can help to promote scientific discovery across the academy and by doing so, identify gaps and weaknesses in our spatial analytic and visualization approaches that geographic information science should tackle in the years ahead. The spatial university is then one that is completely involved and immersed in every facet of this cycle notwithstanding the fact that much of the technology innovation occurs outside of the academy. The key markers for such an institution will include a strong geographic information science teaching and research enterprise, numerous collaborations with open source and proprietary software developers, and a large and varied geospatial infrastructure to promote and support multi-disciplinary use of spatial analysis, modeling and visualization in research, service, and teaching across the academy.

The third of these arguments focuses on the unique character of the spatial sciences and the need to cover both fundamental science and practical skills in our teaching programs. This can be viewed as a strength (for example, our students find jobs upon graduation) or a weakness (with perhaps the most common being the claim that we teach our students to navigate software without providing the critical thinking skills to use these tools appropriately) and the goal therefore must be to build learning environments that support fundamental science (i.e., the spatial concepts and methods that facilitate spatial analysis, modeling and visualization) and the various ways that individual software tools can be used to produce certain outcomes. In addition, I believe that these environments will work best if they cover the entire geospatial workflow (from spatial data acquisition to analysis and visualization and the communication of the results with various audiences) and if they support multiple entry and exit points to accommodate students with varied interests and goals.

Given this background, I think that the immediate challenge is to find ways to build academic programs on individual campuses that both mirror and celebrate these fundamental truths. The best “spatial” universities in 2025 will need to provide multiple gateways that

promote spatial thinking (i.e., competency) and lead to a series of more sophisticated learning opportunities that will inevitably span many disciplines and application domains. These pathways will almost certainly incorporate a strong geographic information science presence in geography or some other department but the present-day character of our universities and the journey traversed by myself and others over the past quarter century suggests this is the easy part! The more difficult tasks have to do with first, the initial entry points that build spatial competency and may or may not lead to the aforementioned geographic information science programs and second, how geographic information science might be deployed to support creative spatial thinking across the whole university.

I think everyone attending this meeting probably agrees that the gateways should focus on freshman and sophomores and that they might take one or more of several forms. One answer is to include a “Spatial” requirement in General Education Programs and indeed, several participants in a recent blog hosted by Esri argued that not much progress could be made to create truly “spatial” universities without the inclusion of this element. Others, including some of the participants attending this meeting, have taken a slightly less ambitious approach and created spatially-inspired General Education classes that fall into some established rubric (i.e., under the Science & Technology banner, as I have done at USC) and attract 100-200 student every time they are offered. The problem here is one of reach and scalability since this approach is never likely to engage a large fraction of the student body. A third approach and one that we are about to roll out involves a series of two-unit courses that focus on specific disciplines and application domains (i.e., GIS & Diplomacy, GIS & Health, GIS for Design, GIS for Business, etc.), utilize the technology of choice among today’s students (i.e., mobile phones and tablets), and push geographic information technologies ahead of the underlying science as a way to get more students engaged in thinking spatially about questions and topics that interest them.

This last approach can then be bundled as part of a broader initiative to build from a broad base to multiple pathways that span many schools and departments (and thereby, to help achieve the second of the two goals noted above). These collaborations must involve more than the sharing of hardware and software and the format cannot one in which multiple departments offer what is essentially the same introductory course (as often happens now) since this is a waste of resources (and over the longer term, a wasted opportunity). The goal must be to capture and use some of these savings to establish and sustain more meaningful research, service, and teaching collaborations across the affected schools and departments. This is perhaps the hardest task of all because there often will be budget and personnel implications that follow from the pursuit of this kind of strategy. The challenge then is to build an inclusive framework and to organize it in such a way that all of the participants get some benefit from the university’s spatial enterprise that is more or less commensurate with their contribution.

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## Perspective on Spatial Thinking Across the College Curriculum

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Southwestern College has a geospatial science and technology program that is designed to serve two student cohorts: **1)** Those seeking a career within geospatial technologies; and **2)** Students in an ancillary “spatial” discipline (such as business, economics, criminology, environmental science, math, engineering, political science, social science, physical science, etc.) in which geospatial technology and spatial thinking coursework will strengthen their academic and career “toolset.” *Geospatial* is a growing occupation and becoming more of a pervasive tool across a variety of industries and applications; we want our program to serve those needs.

Our recruitment strategy for the program has been twofold. First and foremost, we created a GE (general education)—satisfying introductory geospatial awareness and spatial literacy course that fulfills a variety of graduation requirements (including Computer Literacy, Language and Analytical Thinking, Interdisciplinary Social or Behavioral Science, and Mathematics and Quantitative Reasoning). The course has the following, basic objectives:

- 1) Introduce geospatial technologies (including career opportunities in the geospatial industry) to a large and diverse cohort of students;
- 2) Recruit more students into GIST programs (once in the course, the “newbies” will be so fascinated with the topic—including the concept of spatial thinking and its importance—that many of them will choose to continue their respective GIST program;
- 3) Once a GE course, seek other programs on campus to include it in their core curriculum (for example, at SWC, the GE-GIST course is core curriculum within the Urban Development and Business programs); and
- 4) Simply offer a quality course in spatial literacy. Spatial thinking is integral to the success of all students, yet it’s a topic that has been historically lacking in education (at all levels).

Certainly, subtle acknowledgement of the need to be spatially aware has existed within spatial disciplines, however direct instruction on how to spatially *think* has not been a part of traditional curriculum. As Michael Goodchild so eloquently put it, “spatial literacy is a set of abilities related to working and reasoning in a spatial world and to making a picture truly worth a thousand worlds. Children grow up to function as adults in a world in which the three Rs—reading, writing, and arithmetic—are considered essential as much to basic functioning as to the realization of life’s higher objectives. Today, we surely have to add spatial literacy to the list” (Goodchild, 2006).

Our GE course (entitled *Geographic Information Science and Spatial Reasoning*) focuses upon spatial thinking, spatial awareness, and how geospatial technology is being implemented

across a variety of disciplines. The course attracts over 100 students annually. It is important to note that, largely due to this course, the diversity of our student cohort remains relatively high. The female enrollment of our GIST GE course is typically 40% to 60%. According to a 2009 survey conducted by the GeoTech Center (<http://www.geotechcenter.org>), female enrollment in a non-GE GIST course is typically 25% to 30%. As one would expect, a general education course offering has the added benefit of attracting a more diverse student population (including underserved and underrepresented groups) into geospatial science and spatial literacy courses.

Our second method of recruitment is to “seed” geospatial and spatial reasoning curriculum within a variety of academic disciplines across the campus. By introducing geospatial learning module(s) into a diverse set of courses we are effectively introducing students to spatial thinking and exposing them to how geospatial technology is a part of “their” discipline. Spatial-thinking learning modules (using tools such as Google Earth, ArcGIS Desktop, ArcGIS Explorer Online, and a variety of Internet sites) are now being employed on our campus within 8 unique disciplines (in approximately 50 sections), touching more than 2,000 students annually (and this number is growing every semester).

Perhaps one of the best ways to tackle the lack of spatial thinking in college curriculum is to add “Spatial Literacy” to the list of GE categories. A Spatial Literacy GE category, along with the augmentation of spatial thinking modules into present curriculum, would go a long way to minimizing the spatial teaching gap at the collegiate level. Of course, the list of graduation requirements for students has seemingly been growing over the past decade. Short of creating a Spatial Literacy GE category, another option is to do as we did at Southwestern College: create geospatial awareness and spatial thinking coursework that satisfies a number of already established GE categories.

**Reference:**

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# SPECIALIST MEETING— *Spatial Thinking* Across the College Curriculum

December 10–11, 2012  
Upham Hotel  
Santa Barbara, California

## Objectives:

There is now convincing evidence that spatial abilities are related to both success and participation in STEM disciplines. More generally, there is an increasing recognition of the importance of spatiality as a unifier of academic disciplines, including the social sciences, arts, and humanities, sometimes referred to as a “spatial turn.” But it is also widely acknowledged that spatial thinking is not fostered in our educational system and that current practice depends more on selection of the most able students for spatially demanding disciplines than on fostering the spatial intelligence of all students. This meeting will bring together cognitive scientists, disciplinary experts, and college administrators to examine how to best educate spatial thinking at the college level. An overarching goal will be to prioritize a research agenda to evaluate current approaches to spatial education, fill gaps in our knowledge, and consider how a curriculum in spatial thinking can best be implemented at the college level.

## Meeting Structure:

This 2-day specialist meeting is organized by the Center for Spatial Studies (<http://spatial.ucsb.edu>) at the University of California, Santa Barbara, and the Spatial Intelligence and Learning Center (<http://www.spatiallearning.org/>). The meeting will include invited plenary presentations by experts on challenges of spatial thinking in different disciplines, cognitive analyses of spatial thinking processes, and current best practices in educating spatial thinking. In smaller breakout sessions, disciplinary experts, cognitive scientists, and college administrators will work together to identify the

## Call for Applications:

To respond to this announcement, please send a 2-page résumé and a 2-page position paper discussing your interest in these issues to Mary Hegarty ([hegarty@spatial.ucsb.edu](mailto:hegarty@spatial.ucsb.edu)) by **September 24, 2012**. Participants will be selected by the organizing committee and notified by October 12. Subject to approval, limited funding for travel and accommodation costs will be available to invited participants. Further details about this meeting will be posted at:

<http://www.spatial.ucsb.edu/events/meetings.php>

current state of our understanding of spatial thinking, identify gaps in our knowledge, and identify priorities for both research and practice in educating college-age spatial thinkers.



## Organizing committee:

Mary Hegarty,  
Mike Goodchild, &  
Don Janelle  
Univ. California, SB  
Nora Newcombe &  
Thomas F. Shipley  
Temple University  
Diana Sinton  
Univ. of Redlands

## Questions to be addressed include:

- What are best current practices in spatial education at the college level?
- What is the role of technologies, such as geographic information systems and virtual environment technologies, in developing spatial thinking skills?
- Can we identify a set of general spatial skills that are relevant to spatial thinking across several disciplines?
- Are spatial skills best trained in the context of a discipline or in a more general context? For example, if a student is taught to imagine cross sections in the context of a geology course, does this skill transfer to imagining sections in engineering or biology?
- What are the connections between “spatial thinking” courses and curricula organized for disciplines? For example, do all geography or geometry courses naturally or automatically support spatial thinking processes?
- What are learning outcomes for spatial thinking curricula, and what form should assessment take?
- What are the administrative challenges and opportunities for implementing spatial thinking courses and programs at the college level?