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Spatial Thinking across the College Curriculum, Final Report

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Spatial Thinking Across the College Curriculum

Specialist Meeting

Final Report

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Upham Hotel
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This specialist meeting was convened and funded by the Center for Spatial Studies at the University of California, Santa Barbara (Mary Hegarty, Director) and the Spatial Intelligence Learning Center (Nora S. Newcombe of Temple University, Director), with additional funding from Esri (<http://esri.com>).

Executive Summary and Introduction

This 2-day specialist meeting was conceived and organized by The Center for Spatial Studies (spatial@ucsb) at the University of California, Santa Barbara (UCSB), and The Spatial Intelligence and Learning Center (SILC), based at Temple University. **Spatial@ucsb** is dedicated to promoting campus-wide spatially related events, research, and teaching for all disciplines that share interest in the importance of spatial thinking in science and in artistic endeavors, the development of spatial analytic tools, and the importance of place in society. **SILC** is a multi-campus NSF-funded initiative that brings together scientists and educators from many different institutions to pursue the overarching goals of understanding spatial learning and using this knowledge to develop programs and technologies that will transform educational practice, helping learners to develop the skills required to compete in a global economy.

The **Organizing Committee** for the meeting included Mary Hegarty, Michael F. Goodchild, and Donald G. Janelle from spatial@ucsb; Nora S. Newcombe and Thomas F. Shipley from SILC; and Diana Sinton (University of Redlands). Funding from SILC, spatial@ucsb, and Esri is gratefully acknowledged.

The call for participation in the meeting included the following **statement of purpose**.

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. An overarching goal [of this meeting] 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.

All participants in the meeting prepared position papers in response to some or all of the questions listed below. These position papers represent an important set of ideas about spatial thinking in the college curriculum and may be accessed at

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

Questions for Consideration:

- What are best current practices in spatial education at the college level?
- What role do technologies, such as geographic information systems and virtual environment technologies, play 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 domain of general knowledge? 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?

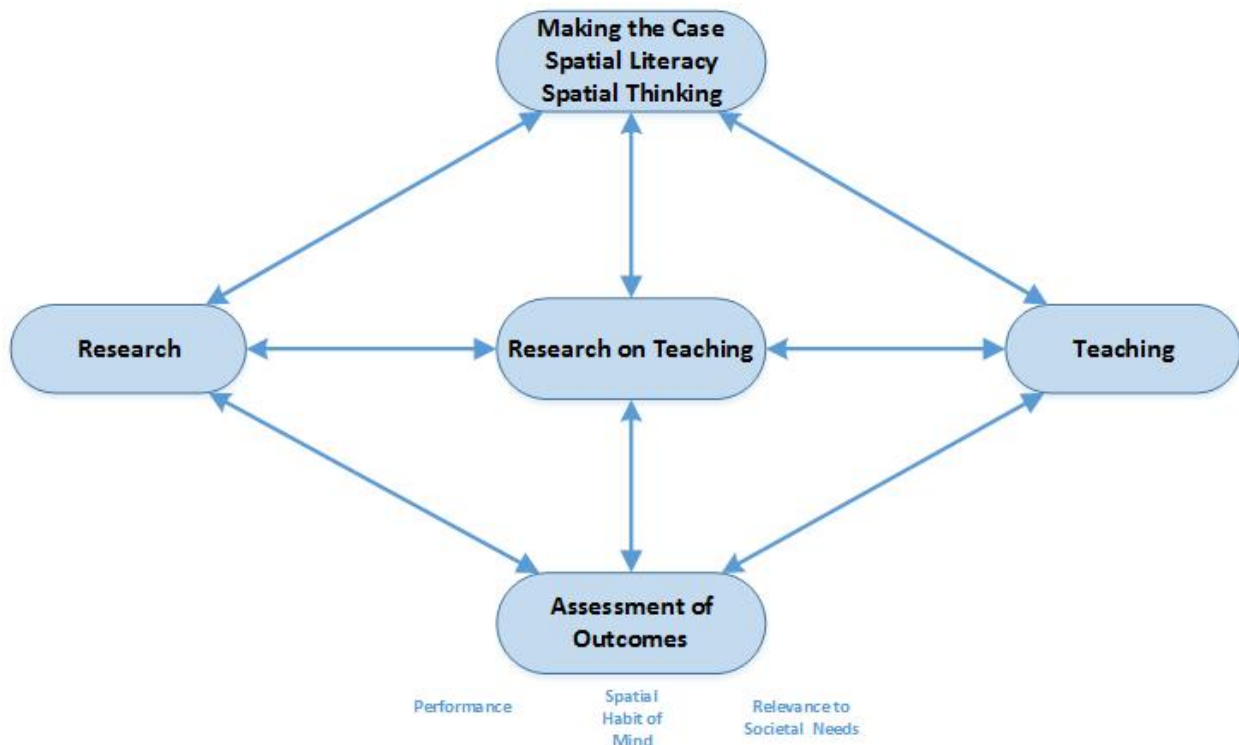
- What are the connections between “spatial thinking” courses and curricula organized for disciplines? For example, do all geography or geometry courses naturally or automatically support spatial thinking processes?
- What are learning outcomes for spatial thinking curricula, and what form should assessment take?
- What are the administrative challenges and opportunities for implementing spatial thinking courses and programs at the college level?

Structure of the Meeting

The meeting featured plenary presentations by experts on the 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 worked together to identify the current state of our understanding of spatial thinking, gaps in our knowledge, and priorities for both research and practice in educating spatial thinkers at the college level.

Full details about the specialist meeting, including a participant list, short position papers from participants, copies of presentations made during the meeting, and additional materials (including this report) can be found at <http://www.spatial.ucsb.edu/events/STATCC/>.

Summary of Primary Findings and Outstanding Issues



Making the Case for Space

In recent years, there has been a massive increase in spatial availability and accessibility of spatial representations and technologies. Using technologies such as Google Earth and the Global Positioning System is now an everyday occurrence. While space has always been central to many basic sciences (e.g., physics, chemistry, and geology), there is an increased emphasis on spatial analysis in the sciences with projects such as gene mapping and brain mapping. At the same time, increasing attention is given to space in the humanities and social sciences, and it is heard in everyday discourse as well. One prominent example is that maps and spatial analyses are now commonplace in reporting of election results.

At the same time, global challenges facing humanity are spatial problems—such as resource distribution and climate change. We must educate students in spatial thinking to facilitate their ability to address these basic problems. More generally, as our culture becomes more spatial, we should educate students to capitalize on the use of visual-spatial representations in all human endeavors.

However, in contrast to literacy and mathematical thinking, spatial thinking is not currently fostered in our educational system. We believe that spatial thinking approaches will enhance and enrich learning experiences across higher education, but we face several challenges in implementing this goal: **1)** Spatial thinking is fundamentally cross disciplinary, so that we face difficulty implementing such a program in our current college system, characterized as it is by disciplinary silos. **2)** The nature of college education is changing, with increasing constraints on public funding for education and a move to alternative approaches to the traditional lecture format, such as online courses. **3)** In convincing administrators, funding agencies, and colleagues to embrace spatial thinking, we are competing with other approaches to improving the college curriculum, such as the critical thinking movement.

In order to make **the case for space, basic research** must come to a more fundamental understanding of what we mean by spatial thinking, including different varieties of spatial thinking across the college curriculum, and identifying what is common to spatial thinking across disciplines. At the same time we must continue to develop methods of **teaching** spatial thinking where we can, with current resources. Further, we need **research on teaching** spatial thinking, including **assessments** of what is learned from programs that aim to teach spatial thinking. We must also **document and demonstrate** where and how spatial thinking prepares students for academic success and allows them to better compete in the job market and global economy.

Basic Research

While all of the participants at this meeting are studying or teaching spatial thinking at some level, spatial thinking means different things to scholars from different disciplines. There was a consensus that we need a better understanding and articulation of what we mean by spatial thinking or thinking spatially. For example, we must understand the extent to which spatial thinking depends on concepts, skills, or the use of technologies. Different constituent groups at this conference brought with them an understanding of spatial thinking as it is applied and practiced within their discipline, and these distinctions currently hinder cross-disciplinary conversations. One important research goal is, therefore, to explore and adopt a common framework for characterizing spatial thinking.

Another important research goal is to characterize varieties in the nature of spatial thinking across disciplines. To this end, a promising approach that is already being adopted by some

participants at the meeting is “discipline diving,” in which cognitive or learning scientists collaborate with disciplinary experts to observe and study the nature of spatial thinking in different disciplines. To date, this approach has to some extent been adopted in Science, Technology, Engineering and Mathematics (STEM) disciplines, but while continuing to study these disciplines, we must move beyond STEM domains to consider spatial thinking across the college curriculum more generally.

Finally, although spatial thinking takes somewhat different forms across the college curriculum, participants at the meeting also believed that there are core concepts and skills that are more domain-general, thus, another important goal of research is to identify these core concepts. For example, candidate core concepts included distance, dispersion, scale, spatial dependence, and spatial heterogeneity; core skills might include proficiency in designing and critiquing alternative spatial representations and in using spatial technologies.

Teaching

There was also consensus at the meeting that educating spatial thinking should not wait until we have more fundamental understanding. There are already several promising approaches to teaching spatial thinking that are implemented at different colleges and universities, and attempts to teach spatial thinking can also feed into a fundamental understanding of the nature of its nature. Current approaches include general education courses, spatial minors, freshman seminars, and micro insertions within existing courses (such as a lecture or demonstration on some aspect of spatial thinking). Meeting participants agreed that we should continue to teach spatial thinking where we can within the current resource and organizational constraints and structures of our institutions. In addition, there was interest in developing a massive open online course (MOOC) in spatial thinking.

Research on Teaching

Although we believe that current attempts to teach spatial thinking are effective, we have little objective evidence for this and we are not currently in a position to advocate a best approach or set of approaches for teaching spatial thinking across the college curriculum. For example, we do not know whether spatial skills are best trained in the context of a discipline or whether it is more productive to identify core spatial concepts and skills and teach them in domain general courses. The issue of transfer of learning is critical here. Specifically, we need basic research on how to teach spatial thinking so that it transfers across different disciplines, as well as how to teach the specific spatial concepts and skills that are relevant to particular disciplines. We must also better understand when to use each of these approaches, as there is a consensus that one approach does not fit all circumstances. Basic research on the nature of spatial thinking can inform our educational goals; however, as we adopt different approaches to teaching spatial thinking, we must also assess and evaluate what is learned.

Evaluation and Assessment

There is currently solid evidence that there are specific spatial abilities and skills (e.g., spatial visualization) that predict performance in STEM disciplines and that these spatial skills can be trained. However, research to date has focused on skills for which there are well-developed assessments (e.g., mental rotation), rather than developing assessments of the concepts and skills that we believe are most central to spatial thinking. As we develop better characterizations of the nature of spatial thinking, we must also develop means of assessing spatial thinking, including

assessments of spatial concepts and skills that are important in disciplines besides STEM. For example, many participants in the meeting endorsed the goal of developing “a spatial habit of mind” in students. Although challenging, we need to develop a means of assessing our success in meeting such broad goals in order to build a body of evidence for the importance of educating spatial thinking across the college curriculum.

Finally, we must gather data on the future careers of students who participate in different spatial thinking programs, to provide evidence for any advantages that a spatial education gives to students in their future studies and in the global job market.

Day One: Invited Presentations

Mary Hegarty opened the meeting, reviewing briefly its objectives and format, acknowledging the important work of the Organizing Committee, support from the sponsoring organizations (spatial@ UCSB and SILC), additional funding through David DiBiase from Esri, and the administrative and logistical support provided by Karen Doehner.

Day 1 was organized around four sessions. Each session included invited presentations, followed by comments from a designated discussant and open discussion about issues.

Session 1: Defining the Need for Spatial Learning

Roger M. Downs, Pennsylvania State University
Making a Place for Space

Downs' presentation grounded the purpose of this meeting around a set of key questions and the need to advance a "Case Statement" that provides the rationale, justification, and strategy for further promoting the cause of spatial literacy in education. His questions were fourfold: The rationale for the broad mix of researchers and educators present (why us?); the understanding of why such a meeting is relevant now; the articulation of problems that we might resolve; and the need to anticipate the questions of audiences that should be part of such a discussion. For example, how do we resolve ambiguities between "spatial thinking" and "thinking spatially," or between "spatial skills" and "spatial intelligence"? If this is important, why have we not paid attention to it before now? And, where does/should spatial thinking reside on campus?

The **case statement**, a central focus of Downs' talk, must have a goal, a rationale, recognition of challenges, and a model for implementation. For example:

Goal—every student should graduate with a working understanding of the theory and practice of spatial thinking.

Rationale—spatial thinking is an essential underpinning to life in the physical and virtual worlds. Geospatial tools and technologies are integral to everyday life, business, research, and government. Students must be informed, wise, and ethical in their use of a wide range of spatial thinking tools.

Challenges—move beyond discipline-based structure of education systems and funding agencies; address the deceptive obviousness of spatial thinking as reflected in its current minor role in the college curriculum; build a rationale for the centrality of spatial thinking to business (moving beyond the obvious case of GIS); and cultivate a recognition of its importance in civic life.

Models for Implementation—review models of societal change for mobilizing interest in the value of promoting spatial literacy; consider supportive activities (e.g., and marshal evidence on the benefits of acting and the costs of not doing so; assess the results of parallel efforts (e.g., see <http://www.brainnet.org/images/decadelogo.gif>); take advantage of promotional opportunities (e.g., public symposia and TV programs, op-ed columns); and identify possible entry points and replicate successful implementations into the college curriculum (examples might include the general education course offered by Peter Bol and Kirk Goldsberry at Harvard University, online

programs at Penn State University, and the introduction of academic minors in spatial studies/thinking at UCSB and the University of Redlands).

Nora Newcombe, Temple University
Creating a Science of Spatial Learning

Newcombe’s presentation reviewed evidence that spatial skills and spatial learning are important in the science, technology, engineering, and mathematics (STEM) disciplines, specifically, and in human functioning, more generally. For example, there are sex differences and SES differences in spatial skills, and it is important for social equity to address these differences.

She reviewed evidence that participation in science disciplines in adulthood can be predicted by spatial ability in high school, discussing the malleability of spatial skills, including a recent meta-analysis showing that these skills can be trained in adults and that this improvement is durable and transferable. She also summarized evidence showing that training spatial skills can generalize to STEM learning. For example, training spatial skills in early childhood leads to better outcomes in mathematics classes, whereas training adults generalizes to improved performance in physics, chemistry and geology classes.

Newcombe delineated techniques for effective spatial training, including learning from external symbol systems, from spatial alignment and analogy, and from action to abstraction. Finally, she outlined challenges for the future: characterization and assessment of spatial skills, continuation of controlled laboratory studies with larger-scale interventions in classrooms, representation of mechanisms more finely, and understanding what techniques work best in different contexts.

Kim Kastens, Education Development Center
Discussant

Kastens encouraged the audience to consider a broader picture of higher education in America. If universities, parents, students, and taxpayers continue to face the increasing financial burdens of providing/securing education, one could possibly advance the cause of spatial literacy through innovative MOOCs and self-help tutoring. Such options and other “Big Plans” should be based on identifying where the need for spatial education exists. We can adapt to global challenges, the changing nature of college education, and the expense by moving to online courses. These experiments should be paired with collecting data on the experiences of instructors/students and scientific assessment of the learning outcomes. If we believe that every student should graduate with a working understanding of the theory and practice of spatial thinking, we must heed Downs’ concern for developing a case statement, recognizing that spatial competency is competing with other approaches to improve the college curriculum.

Identifying the problem(s) that a spatial focus will solve is critical—insufficient learning in STEM? People getting lost? Whatever it is, the problem must be one that the audience thinks is important—e.g., college leaders may perceive the problem as declining enrollments or cost of implementation. Newcombe documented how spatial thinking is both important and teachable, stressing that we must also consider how spatial thinking should be prioritized relative to informative and persuasive writing, quantitative thinking, critical thinking, or other worthy educational objectives. We must know the intellectual competition. Successful implementation requires more than just institutional models; we also need pedagogical models and audience

models. A case statement for spatial learning should address both the benefits and costs of acting, and the penalties and costs of not. See Kastens' prepared statement at <http://www.spatial.ucsb.edu/events/STATCC/docs/Kastens-presentation.pdf>.

Session 2: Challenges of Spatial Thinking across the Disciplines

Lynn S. Liben, Pennsylvania State University

Spatial Education across the College Curriculum: A Psychologist's Perspective

Lynn Liben's talk focused on four topics: spatial content, developmental insights, interdisciplinary partnerships, and future directions.

In terms of spatial content, Liben pointed out that the community must reach a consensus on what spatial thinking is and what should be taught. For example, should we teach spatial skills, technologies, and/or conceptual systems? Examples of different frameworks for spatial thinking included Piaget's distinction between topological, projective, and Euclidean geometries; Hagen's representational geometries; and a taxonomy identified by the TeachSpatial project. Regardless of what we choose, we should identify (articulate) systematic spatial structures to organize spatial instruction and foster students' understanding of those structures.

Next, she argued for looking to developmental theory and research to identify target challenges in spatial thinking, with examples from some of her work on the water-level task and development of projective geometry.

Liben then called for collaboration between learning scientists and STEM-content experts, giving examples from her own work with geoscientists, in which she identified a range of spatial thinking processes used by geologists on an everyday basis, and specific spatial challenges in understanding concepts such as strike and dip.

For future directions, Liben stressed that we need to design, implement, and evaluate interventions at both general (overarching spatial structure) and precise (specific STEM content) levels simultaneously. She also recommended that we attend to affective (motivational) as well as cognitive factors and take developmental insights into account. Finally, she proposed that we build new professional roles of "spatial curriculum specialists" to work collaboratively with STEM educators to identify and respond to learner needs for specific content.

Peter K. Bol, Harvard University

A View from History and the Humanities

The concept "space" and spatial analysis permit understanding of variation across space. This is important but, in the humanities, history "takes place" in places—named locations whose histories are created locally. Bol contrasted space and place perspectives on Chinese history as applied to interpretations of China's first geographic text—*The Tribute of Yu*—and its descriptions of China's Nine Provinces/Regions and Five Divisions in relationship to *The Treatises on (Administrative) Geography* in the country's dynastic histories. He gave examples of the spatial turn in history, including the China Historical GIS and the mapping over several centuries of individuals whose demographic and social characteristics are temporally and spatially geo-coded in the China Biographical Database. He demonstrated the uses of GIS-based maps for visualizing spatially large quantities of historical data about regions and places to

reconstruct China’s changing human landscapes at different geographical scales through time. This provided an opportunity to consider the infrastructural needs of the humanities for creating and exploiting large geo-referenced historical data sets. Although progress has been made in the use of GIS and web technologies for creating and searching online archives of maps, the development of federated geodata systems and online mapping repositories still face cyber-infrastructure obstacles that impede the use of spatial thinking and related technologies in the discipline of history.

A foremost necessary contribution to advancing the use of mapping and spatial thinking by humanities scholars is a world-historical gazetteer, which, at its simplest, is a listing of place names with their locations in space. If online gazetteers are enhanced to record the time when changes in the names of places and their boundaries occur, this would create a bridge between history’s place and geographical information science’s space perspectives. Extracting vector data from historical maps could populate a world-historical gazetteer; however, this requires either the extension of optical character recognition technology or successful crowd sourcing of the laborious manual extraction of data from scanned maps. These efforts are underway. But, for the time being, georeferenced map scans remain the most important source for historical information about space and place. Examples of projects that help in the sharing of geo-spatial historical data and maps include Old Maps Online (<http://oldmapsonline.org>), the Open Geo-portal (<http://OpenGeoportal.org>), the World-Historical Dataverse of the Center for Historical Information and Analysis at the University of Pittsburgh, Esri’s ArcGIS Online, and Harvard’s WorldMap (<http://worldmap.harvard.edu/>). The Center for Geographic Analysis at Harvard is developing the WorldMap platform for users to explore, visualize, edit, and publish geographically referenced information, and to build an accumulation of spatialized data that can be shared—making it possible and easier to think spatially by combining and mapping data layers online.

Michael F. Goodchild, University of California, Santa Barbara
A GIScience Perspective

Geographic information systems have developed over the past 40 years and are now able to perform any conceivable manipulation of geographic data. Options have increased exponentially. Goodchild argued that this increasing capability has compromised the ease of learning, and using GIS and has increased the likelihood of its misuse. He presented applications of maps that illustrate a fundamental misunderstanding of basic spatial concepts (e.g., scale, bounded regions), then focused on the need for students and researchers to understand and use such advanced spatial concepts as “spatial dependence” (nearby things are more similar than distant things) and “spatial heterogeneity” (i.e., that the results of any analysis depend explicitly on the geographic bounds of the analysis). He suggested that since such concepts affect and have implications for analyses and statistics, it would be strategic to identify and promote situations where overlooking or mis-applying spatial understanding has led to errors, mistakes, and other such consequences.

Goodchild noted that the most widely applied commercial GIS software, ArcGIS (version 10), includes 615 functions in its Toolbox, organized incrementally over time into a complex non-intuitive structure for mapping and spatial analysis. Reorganizing the toolbox in support of critical spatial thinking might stress the fundamental spatial concepts of spatial thinking and

spatial analysis (see <http://teachspatial.org>), formalizing the functions with support from concept taxonomies established by leaders in GIScience (e.g., J.K. Berry, J. Dangermond, D.J. Maguire, and D.W. Rhind). All functions in the GIS toolbox should allow one to explore and evaluate a basic concept (e.g., distance, direction, measures of relationship between layers, etc.) and its expression in a given data set. It should be based on a systematic study of the nature of geographic information, principles implemented in geographic information systems, and practices of reasoning from geographic information; additionally it should support what goes on in the minds of a critical spatial thinker. Re-arranged in these ways, GIS may become more intuitive to use, more cleverly applied, and less likely to be misused.

Karl Grossner, Stanford University

Discussant

We must define spatial terms (e.g., spatial thinking/ ability/skills/literacy/reasoning), enumerate the overarching set of concepts to be mastered to produce an “integrated conception of space,” and learn from other disciplines’ efforts to promote writing, numeracy, graphicacy, and critical thinking. Spatial thinking is an amalgam of concepts (knowledge), tools (spatial representations), and reasoning (ways of thinking), but it is also, as Peter Bol notes, “an attitude.” Candidate goals for determining the benchmarks for spatial literacy might include being conversant with core spatial concepts and principles and their application in multiple scientific and humanistic fields (see <http://teachspatial.org>), as well as awareness of the role of spatial thinking in scientific explanation and the “habit of mind” to use it.

Discipline-diving to identify the concepts and practices of spatial thinking used in different fields can draw on work related to geography (e.g., R. and S. Bednarz, R. Golledge, M. Goodchild, D.G. Janelle, W. Kuhn, and D. Unwin) and the geosciences (K. Kastens, L. Liben and S.J. Titus, C.A. Manduca, T. Shipley), to Hegarty’s work with researchers in chemistry (M. Stieff), meteorology, physics, and surgery, and to Gahegan’s explorations of computation across e-science. For historical scholarship, gazetteers and data depositories (spatial infrastructure) are pivotal to demonstrating value. Here the core spatial concepts are space versus place, location, and distance. Grossner referenced several projects in the digital humanities at Stanford University as exemplary of interdisciplinary efforts that apply spatial reasoning to uncover patterns and processes across space and time, including a geospatial network model of the Roman Empire and mapping the Grand Tour of Italy (see <http://www.stanford.edu/dept/classics/cgi-bin/web/projects>). He cited examples of attempts to integrate knowledge through spatial context, such as *Spatially Integrated Social Science* (Goodchild and Janelle, editors), but noted the need to differentiate in order to integrate.

Grossner’s statement, available at <http://www.spatial.ucsb.edu/events/STATCC/docs/Grossner-presentation.pdf>, provides an overview of possible applications of spatial concepts from more than a dozen disciplines, illustrating how the search for explanations of structures and processes require an integrated application of multiple spatial concepts.

Session 3: The Challenges: Spatial Thinking within Disciplines

David DiBiase, Esri

Implementing Spatial Thinking Across the Curriculum

This talk drew parallels to an initiative at Pennsylvania State University to institute an ethics requirement across the curriculum. Although courses and modules were created, the use of micro insertions of ethics content into existing domain-specific learning activities, supported by the SARI@PSU program for Scholarship and Research Integrity, was seen as an effective strategy for sustained success. Since institutional mandates to incorporate spatial thinking in the general education curriculum do not currently exist, progress may rest on this community's ability to demonstrate the benefits of spatial literacy. A starting point may be a broadly conceived and clear definition of what is meant by spatial thinking along with a research agenda to fill the gaps in evaluating its value. But it is also useful to consider the use of micro insertions into existing courses and, especially, general education text books. Taking leading introductory textbooks—*Give Me Liberty! An American History* (Foner, 2005), *Economics* (McConnell, Brue, and Flynn, 2008), and *Psychology* (Myer, 2004)—DiBiase demonstrated the use of micro-insertions, insets of maps, diagrams, and graphics to complement text discussions. He pointed to a way forward to organize, create, curate, and promote the use of spatially explicit micro insertions as a cost-effective way to reach a significantly large number of students across many institutions, and encourage wider appreciation of the value that a spatial representation and/or analysis brings to these disciplines.

In addition to the position papers for this meeting by Tom Baker and David DiBiase, see the conversation in response to their 23 July, 2012 blog on “Envisioning the Spatial University” at <http://www.spatialroundtable.com/post.cfm?entry=envisioning-the-spatial-university>.

David Tulloch, Rutgers University

A Design Perspective on Spatial Thinking

“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.”

Opening with this quote from Michael Graves (2012), David Tulloch outlined the process of design education, which he described as rapid, immersive, sensory, active, and problem-based. Design education is based on the premise that drawing and designing are fundamental to developing spatial thinking. Sensory learning includes seeing, drawing, and building models to create concrete representations of buildings and landscapes as well as abstract creations that are subtly spatial.

Field trips are important in landscape architecture in particular. In the field, the student experience is not only visual, but is also tactile. Again, drawing is important, and shared experiences lead to rich memories that are later used in the design process.

The central component of design education is the design studio. Design studio courses are required core courses that often take place in dedicated spaces that are accessible 24/7, such that the studio is known for late-nights, lost weekends, and unbridled creativity. The design studio involves problem-based learning to address a spatially explicit problem and is extremely collaborative and active.

Developing admissions policies for undergraduate design programs raise questions of whether design (or spatial thinking) is a talent or a skill. Many programs use exams that include tests of spatial thinking and creativity, including drawing and model-construction exercises in addition to standardized tests of visual and spatial acuity. Critical issues are whether spatial cognitive skills are testable without preparation and whether they are universally learnable.

Tulloch concluded with potential informative lessons about educating spatial thinking from the design perspective, including the importance of problem-based and active learning. However design education is time consuming. Tulloch emphasized that it is important to ask what level of preparation students bring to the design studio and whether accreditation would change this. It is also important to consider the issue of transfer, that is, what classes and techniques transfer best, and how does transfer from design courses compare with transfer from courses in geography and other disciplines.

Stephanie Slater, Center for Astronomy and Physics Education Research
Invasion of the Cognitive Scientists: Subverting College Astronomy

Astronomy 101 is taken by more than 250,000 college students per year and 40 percent of all pre-service teachers, often as their sole science requirement. However, research indicates that most students leave this course with little understanding of the earth and universe. This failure of the educational process is well documented, but the cause of the failure is not understood. Stephanie Slater described the work of the Center for Astronomy and Physics Education Research, which is concerned with identifying the cognitive barriers that prevent students from developing scientifically accurate conceptions of astronomy, and with developing more effective instruction on this topic.

Barriers to developing a correct understanding of astronomy include misconceptions about astronomy and cognitive processes that interfere with or limit learning, including cognitive load, spatial reasoning biases, and individual differences in spatial thinking skills.

Approaches to instruction include data analysis and inquiry in astronomy and open inquiry through faded scaffolding. Slater has found that it is possible for young children to perform well on tasks that most college students struggle with. She discussed research on young children in Hawaii where the oral tradition of navigation instruction provides students with a solid understanding of where constellations appear and how they move over time in the sky.

Slater also presented quantitative data showing that performance on spatial ability tests is correlated with performance on the Test of Astronomy Standards (TOAST). She presented evidence that manipulatives improved explanatory thinking in astronomy and that spatial instruction lead to improved understanding of astronomical geography, rotation-related events, and orbit- and tilt-related events.

In moving forward, her group is interested in developing task-oriented instruments for spatial-thinking and, in collaborating with cognitive sciences, to overcome cognitive obstacles to science learning.

Mike Stieff, University of Illinois at Chicago

Spatial Thinking in Chemistry

Mike Stieff presented evidence for the importance of spatial thinking in the undergraduate curriculum. Important spatial concepts in general chemistry (Year 1 of the college chemistry curriculum) include atomic structure, hybridization theory, bonding, and molecular geometry. Organic chemistry (Year 2) includes highly spatial content including stereochemistry, stereoselective and regioselective reactions, and structure-reactivity relationships. Finally, in the later years, structure identification through spectroscopy, quantum mechanics, and group theory depend on spatial representations and concepts. Because of the important spatial content of chemistry it is not surprising that correlations exist between measures of spatial ability and achievement in chemistry, or that sex differences in spatial abilities contribute to sex differences in chemistry achievement. There is also some evidence that training of spatial visualization supports chemistry learning.

Stieff also emphasized that there are multiple alternative strategies for spatial thinking in chemistry, ranging from those that depend on external visualizations and diagrams to those that depend on internal visualization and imagery. He described an intervention study in which different cohorts of students in an organic chemistry class were given training that emphasized analytic strategies, imagistic strategies, or combined training in both types of strategies. Training affected the strategies that students adopted at the end of the course (e.g., those in the analytic and combined training conditions used more analytic strategies) and combined training eliminated sex differences on a 12-item stereochemistry problem-solving test. In conclusion, spatial thinking is a central component of the undergraduate chemistry curriculum; spatial thinking involves multiple strategies and “tools” (e.g., models, diagrams, algorithms); and spatial thinking can be directly taught to increase achievement on discipline-specific spatial assessments.

Mark Gahegan, University of Auckland

Discussion: Space within (and between) the disciplines

Mark Gahegan began by pointing out that the range of scales of space considered across the college curriculum is huge, ranging from the subatomic level (electron, quark, etc.) to the astronomic scale of the visible universe. Although geographers sometimes act like they invented space, the computational explosion in the sciences has led to many fields (e.g., computational chemistry, drug discovery, genomics, and bio-engineering, and early universe cosmology) that use descriptive and analytic systems that are fundamentally spatial. This prompts us to ask, what is the common ground in spatial thinking across disciplines? That is, how do we get to Lynn Liben’s idea of “articulation among spatial disciplines”?

Gahegan showed examples of maps in several disciplines, including protein maps (biochemistry), gene maps (genetics), star maps (astronomy), and cosmological maps that examine the expansion of the universe over time. He also presented an analysis of these disciplines in terms of conception of space (Euclidean, etc.), reference frame, decomposition sampling, measurements, and instances.

Gahegan pointed out that even in disciplines that operate at different scales, geographical metaphors are useful because we all share geographical experiences (they operate at human

scales). As illustrated in his talk, many disciplines have “maps” (and use the term), so micro-insertions in courses, grounded in geographical thinking might actually be a reasonable approach to education in spatial thinking.

In closing, Gahegan questioned why some disciplines are still essentially non-spatial in their outlook, how design fits in, and whether design practices (such as sketching and building models) can be carried over to other disciplines to increase spatial literacy.

Session 4: Models of Curriculum Development for Spatial Thinking Across the College Curriculum

Diana Sinton opened the session suggesting two definitions that have been used while developing the spatial thinking curricula at the University of Redlands:

“**Spatial thinking** is the ability to visualize and interpret location, position, distance, direction, relationships, movement, and change, over space” (Sinton, D.S. 2011. *Spatial Thinking*. In J. Stoltman (ed.), *21st Century Geography: A Reference Handbook*. SAGE Publications, pp. 733–744).

Spatial literacy is the confident and competent use of maps, mapping, and spatial thinking to address ideas, situations, and problems within daily life, society, and the world around us.

Wesley Bernardini, University of Redlands

Developing a Spatial Minor at the University of Redlands

Bernardini described the development of a Spatial Minor to serve students at the University of Redlands, a process that has required the contributing faculty to resolve structural challenges, establish the intellectual foundations for the minor, and deal with discipline-based tensions. In the context of a small liberal arts institution, structural issues included: a diverse, but shallow, pool of faculty with spatial focus; the need to build the minor primarily from existing courses; and the lack of a central department (e.g., Geography) to house the program. Following an unsuccessful attempt to have spatial thinking be considered its own category within the General Education divisions, the organizers developed a proposal for an interdisciplinary minor based on two core courses that would provide a foundation of spatial thinking within the minor—“Foundations in Spatial Thinking” and “Introduction to Spatial Analysis and GIS.” Students would also choose four electives to be drawn from two of three options: **a)** Methods and Representations (Art, Math, Physics), **b)** Culture and Communities (English, Government, History, Religious Studies, Anthropology), and **c)** the Natural World (Biology, Chemistry, Environmental Science). The electives feature courses that teach “graphicacy.” Two central tensions arose in deliberations on the objectives and structure of the minor, summarized as **a)** courses that have “place without space” (e.g., humanities courses grounded in the experience of a place [African Literature; French History]) but that do not employ spatial thinking concepts, and **b)** courses that have “space without place” (e.g., Physics and Mathematics) that teach the structure of space without relating it to a lived experience. The Redlands example provides a possible pathway for implementation at other liberal arts institutions.

Sheryl A. Sorby, Ohio State University/Michigan Technological University

Spatial Skills Training to Improve Student Success in Engineering

Sheryl Sorby's presentation described a one-credit remediation course in spatial skills for engineering students that has been offered at Michigan Technological University (Michigan Tech) since 1993.

To document the need for this course, Sorby reviewed evidence that engineering is one of the most spatially demanding fields, including studies at Michigan Tech showing that a student's score on a spatial ability measure—the Purdue Spatial Visualization Test (PSVT)—was the most significant predictor of success in engineering graphics. For example, students with low spatial abilities experience particular difficulties learning CAD software. Sorby also demonstrated the lack of gender and ethnic diversity in Engineering and suggested that this is linked to spatial abilities. For example, her data indicated that both women and non-represented ethnic groups (e.g., African American, American Indian students) have relatively poor spatial abilities upon entering college.

Since 1993, a 1-credit remediation course in spatial skills has been offered at Michigan Tech; this course has now been adopted at several other engineering schools across the country. The course includes lectures, a workbook and online (multimedia) training in spatial skills (e.g., isometric sketching, rotation of objects, cross sections, and object reflection and symmetry). Taking this course has led to large gains in performance on the PSVT test, and those who participated in the spatial skills training performed better in pre-calculus, calculus, chemistry, and computer science courses than students who did not enroll. They also had higher retention and graduation rates, and this was particularly true for women.

Donald G. Janelle, UCSB

UCSB is Spatial! The UCSB Minor in Spatial Studies

Janelle reviewed initiatives by the Center of Spatial Studies to foster and integrate a campus-wide community of spatial thinkers at UCSB. His talk considered one of these initiatives—the implementation of a Minor in Spatial Studies (<http://www.spatial.ucsb.edu/programs/academic-minor.php>). The minor was approved by the UCSB Academic Senate in late 2010 and has graduated nearly 30 students since then. The development and review process for the minor began in 2009 and engaged interested faculty from disciplines across the campus. Open discussions involved the host department (Geography) and almost two dozen other departments with academic deans of divisions in the colleges of Letters & Science and Engineering. The intent was to adapt existing administrative resources and use frequently-offered courses that feature spatial content so as to minimize both costs for the university and constraints on student access.

Intellectually, the resulting program recognizes the legitimacy of different spatial traditions, offering students a choice of three different paths in which to earn a minor: **1)** Spatial Thinking—optional core courses in Geography and Psychology, plus four electives from 26 upper-division courses from 10 departments; **2)** Space and Place—optional core courses in Art, Geography, and History of Art & Architecture, plus four electives from 44 upper-division courses from 12 departments; and **3)** Spatial Science (students select five upper-division courses from among 96 courses offered by 21 departments. The common required course for all students

is Geography 12 (Maps and Spatial Reasoning). Considerable effort has gone into promoting and building awareness of the minor among students and their advisors—developing a Spatial Minor webpage, publishing a brochure, providing examples of course sequencing to complement student majors and career aspirations, and offering a 1-unit Freshman Seminar on “Thinking Spatially in the Arts and Sciences.” We also seek to engage students in activities outside of coursework—participation in the ThinkSpatial Brown-bag Forum and poster displays of student research in the annual spatial@ucsb.local plenary and poster session. The UCSB model provides a template for possible implementation at other universities.

John P. Wilson, University of Southern California
Spatial Sciences Institute (Spatial @ USC): Models of Curriculum Development for Spatial Thinking Across the College Curriculum

The institutional context for a focus on spatial thinking at the University of Southern California (USC) relates to the university’s attempt to raise significant funding and hire transformative faculty. The closure of the Geography Department was followed a month later (July 2010) with the creation of the Spatial Sciences Institute. Its mission is to service the geospatial needs across many disciplines to link fundamental science with enabling technologies that support scientific discovery. The strategy of Spatial @ USC was to position geographic information science and spatial literacy as supportive of critical scholarship. Correspondingly, three undergraduate courses and ten graduate courses were developed to serve a set of new programs. These include a Minor in Spatial Studies, a B.S. in GeoDesign, online M.S. and Graduate Certificate programs in Geographic Information Science and Technology, and a Ph.D. program in Population, Health and Place. These initiatives serve to: represent alternative pathways and multiple entry/exit points for students; coordinate with USC interests in business, design, and environment; support access through web resources, training workshops, and a GIS help desk to spatial data geospatial technologies for research; and make use of web and mobile environments that enhance opportunities for spatial thinking about the world’s natural infrastructure and human environments.

Spatial @ USC also capitalizes on its locally accessible environments to engage students in project-based research. A small-enrollment course (offered 9 to 12 times per year) on applications of GPS/GIS makes use of an environmental field station on Catalina Island and, in an urban context, students conduct research on the design and use of public spaces, placemaking, and city-wide strategic planning. The USC example draws on leadership for responding to opportunities to embed a comprehensive education and research role for spatial technologies and spatial thinking across the campus.

Ken Yanow, Southwestern College and the National Geospatial Technology Center
Top Problems Generally Associated with Geospatial Courses/Programs

Instructors and departments at community colleges often run into the following problems with their Geospatial courses/programs:

1) low enrollment; **2)** poor retention; **3)** limited resources (and IT support staff); and **4)** limited diversity in the classroom. General Education (GE) offers a possibility for addressing these problems. At Southwestern College, the GE course satisfies a number of graduation requirements

(including core coursework for other majors, such as Urban Development and International Business). In addition, summer workshops over the past four years have been offered to faculty across the academic spectrum. Workshop participants are required to develop one or more spatial thinking learning modules to be shared among the group and to be delivered to their students. As more students are introduced to these learning modules, program enrollments have increased.

The GE course is a “spatial thinking” course, with a focus on problem solving, critical thinking, and geospatial thinking skill-development. The curriculum is accessible and is not on-campus lab-dependent. The Southwestern College curriculum focuses on concepts and problem solving. Students complete a series of Internet-based learning modules (free and easily accessible). Such innovative focus on spatial thinking in two-year colleges will impact the entry competency of students to four-year universities. As such, this example provides a basis for collaboration between two-year and four-year institutions.

Day Two: Breakout Sessions and Group Reports

Group 1:

Group Members: Scott Bell, Laura Carlson, Beth Casey, Roger Downs, Eric Fournier, Don Janelle, Robert Kolvoord, Krzysztof Janowicz, John Pani, Tim Shipley, Sheryl Sorby, Mike Stieff, David Tulloch, Ken Yanow

Phase 1: Moderator—Laura Carlson; **Recorder**—John Pani; **Reporter**—Scott Bell
What do we know? What do we need to know? Framing the Research Agenda

This report is structured around a diagram proposed by Roger Downs: the Reasoning/Representation/Understanding triangle. Each of these terms is accorded equal weight. “Understanding” refers to deep levels of comprehension, where we reserve “representation” for more formal systems used by people. The identification/extraction of the essential elements from reality to include under spatial representation is in many respects discipline-specific. Spatial ability will mean different things for different disciplines. One approach to capturing the reasoning and understanding required and afforded by spatial knowledge might be gained through research directed to specific workplace environments and professions, observing and evaluating how the use of spatial technologies improve performance, and taking this back to the classroom.

The group recognized that spatial skill/literacy serves multiple purposes in different contexts and that several models of problems and curricula may be required. Related questions focused on general versus discipline-specific concerns over what is taught at different levels in the curricula and on job training and the importance of spatial thinking for employment.

Polling the participants about defining the important spatial understandings that should be included in a general spatial curriculum, elicited the following responses: proficiency in spatial analysis and description to differentiate the parts of a system; in chemistry, knowing how something will be positioned and oriented after a transformation; working in different numbers and sets of dimensions; understanding spatial heterogeneity; the ability to sketch things; making sense of the world around us; to know how to use abstractions at different scales and in different situations; awareness of the cognitive biases we bring to spatial thinking; the ability to communicate with language and gesture; the ability to understand events through the use of spatial logic for reasoning about the causal narratives of a field; understand that spatial reasoning is an intrinsically spatial processing system with its own capabilities and limits; and, the ability to see the relationship between pattern and process.

New spatial technologies are emerging quickly and students are using them; it makes sense to introduce these technologies into the curriculum without waiting for research to assess their value. The research questions are many and curriculum development should not be held back for lack of definitive understanding.

All fields can be defined in terms of spatial descriptions and operations; even fields that are not intrinsically spatial (e.g., English) can benefit from the power of spatial representation. Nonetheless, there are non-spatial alternatives for most topics that are also important, and often

there is a tension between the two approaches, as in math or computer graphics. While everyone is to some extent a spatial thinker, we differ in how far it extends. Gender differences, training, and experiences may differentiate who can do what.

We have a gap between practitioners who seek concrete learning results and the cognitive psychology approach that seeks fundamental understanding. Maybe this should be defined as classroom versus research approaches. How close are the goals and research agendas of each? Are people who establish curriculum change doing the same thing as doing basic research on spatial ability? How much useful sharing of information is there? How useful to the more pragmatic outcomes is the basic research? One good bit of common ground for research is the question of generalization between courses. For example, would spatial training in one discipline (e.g., engineering) allow students to transfer this learning to other disciplines (e.g., chemistry)? Would a general course on spatial thinking help people with low spatial ability do better? These are open questions that deserve attention.

Phase 2: Moderator—Eric Fournier; **Recorder**—Robert Kolvoord; **Reporter**—Beth Casey
Framing an Undergraduate Course Syllabi and / or Program Curriculum

The question of transferability of spatial instruction and outcomes is open for research and was debated in the group discussion. To simplify the task, this group concentrated on the learning outcomes associated with representing space in a general education lower-division course.

Many kinds of representations exist across disciplines (e.g., mental models, maps, sketches, diagrams). For a general course, we would need to have students understand how different properties of representations might be useful in different disciplines. Students should be able to select and apply (demonstrate, reproduce, construct) appropriate representations for a given problem and translate between representations as needed.

For assessment of learning, students would be expected to demonstrate the use of representations in a variety of contexts, to transfer their uses in a new context (similar/near and dissimilar/far), and retain these skills over time. Why might a general course in spatial thinking be of value and why do we need more spatially literate students?

- For science and society, the goal for such a focus would be to **1)** provide more spatially able students for STEM majors and other programs and **2)** enable citizens to acquire the spatial literacy necessary to function effectively in the current technologically infused society.
- For the students, we must present a clear and compelling rationale for the importance of spatial literacy and relate how it is personally meaningful to them.
- For the university, the Dean must know the purpose (how this solves a problem or opens an opportunity), scale (course? program? major?), justification (supporting research and data), expected outcomes (possible measures), and resources needed.

Group 2:

Group Members: David Bodenhamer, Helen Couclelis, David DiBiase, Fiona Goodchild, Karl Grossner, Stephen Hirtle, Werner Kuhn, Lynn Liben, Rich Mayer, Dan Montello, Nora Newcombe, Sarah Perez-Kriz, Diana Sinton, Stephanie Slater, John Wilson

Phase 1: Moderator—Stephen Hirtle; **Recorder**—Sarah Perez-Kriz; **Reporter**—Dan Montello
What do we know? What do we need to know? Framing the Research Agenda

Although it is useful to consider taxonomies and typologies of spatial concepts and spatial skills, it is a difficult undertaking and we must not wait for a consensus in terms before moving forward in implementing curriculum. Nonetheless, more evidence-based research on the long-term and durable effects of education on spatial thinking (including transfer and persistence) is necessary. The following are among the issues requiring research:

- What types of psychometric spatial tests would be useful and appropriate to determine relationships between the use of GIS and spatial thinking abilities; how use of GIS changes one's spatial thinking; and how performance on psychometric tests predict one's ability to learn/use GIS. Skeptical interest was expressed in the adequacy of GIS for a general spatial education. A general concern is that GIS—although important—cannot itself support all that we want students to learn as critical spatial thinkers.
- Researchers must determine what spatial skills students acquire at different stages through, for example, the use of common information technologies (e.g., cell phones, video games, Google Maps). Identification of what spatial abilities students have upon entry to the university would be valuable in assessing the advantages of generic versus discipline-focused courses to enhance spatial literacy and awareness, and in considering issues of transfer within and across disciplines and the need for sequencing of courses.
- In conjunction with curriculum development, research on the assessment of learning outcomes by students is needed.
- In addressing the issue of whether it would be better to focus on domain-specific or domain-general approaches to spatial learning, most discussants favored a combined approach, seeing a pure domain-general approach as not feasible. However, too specific an approach on a specialized knowledge domain may obscure the value of seeking general principles. For example, distance is a general concept even though its use and measurement varies across different disciplines. Research on how spatial concepts (e.g., scale), representations, and spatial tools (e.g., graphs, maps, etc.) are used in different disciplines might help to draw out the general versus specific spatiality of the humanities, social sciences, and sciences. The group consensus was that the research agenda must move beyond the predominant focus on STEM knowledge.

Phase 2: Moderator—Diana Sinton; Recorder—Karl Grossner; Reporter—Fiona Goodchild
Framing an Undergraduate Course Syllabi and / or Program Curriculum

The general conclusions were: **1)** either generic or discipline-specific courses could succeed if they are well designed and evaluated; **2)** it is essential to clarify terms (e.g., spatial, visual, etc.) and their distinct meanings in different disciplines; and **3)** a focus on the nature and quality of communication about spatial thinking may help to enhance our ability to recruit faculty and students interested in these ideas. Strategically, it would be helpful to adopt a wider level of advocacy for spatial thinking by talking to administrators, professional societies, and employers, and by working at peer levels with faculty and students to communicate the value of spatial perspectives in different disciplines and walks of life.

Much of the discussion focused on alternative ways of building spatial content/awareness into the curriculum and on strategies for implementation at the undergraduate level. Micro-infusions and micro-insertions (e.g., a demo, a lecture) within existing courses were seen as more easily accomplished than, for example, a mandatory general course. Examples presented at this meeting could be adapted sensitively to fit the particulars of individual institutions and their myriad differences (each with a unique mix of schools, professional programs, traditional disciplines, cross-domain committees, centers, and interdisciplinary programs). On individual campuses, one can begin with a survey to identify courses with spatial content, identifying their instructors and academic units as potential collaborators.

Beyond the campus, awareness can be communicated through discipline-based societies but also through broad-based associations such as the American Association for the Advancement of Science (AAAS), which has a long-term interest in science literacy benchmarks. Esri (and possibly other private-sector entities) have an interest in spatial thinking (not just geospatial) and access to a broad audience across academia, industry, and government. Other options for building awareness and general spatial competency include summer institutes for potential instructors and the development of a MOOC, which could involve a geographically dispersed but integrated network of contributing instructors and the potential to reach thousands of course registrants worldwide.

Develop stories of success to reach stakeholders—students, professors, librarians, administrators, and employers. Expect to improve content and spread the word through incremental steps and multiple approaches. The word “opportunistic” arose with some regularity. However, all of these steps could be enhanced through research on measuring the learning outcomes and providing evidence of results (building on efforts, e.g., those demonstrated by SILC) to foster a greater integration of research by teams of discipline-based instructors as well as cognitive science and education specialists.

Group 3:

Group Members: Tom Baker, William Bechtel, Wes Bernardini, Peter Bol, Billy Fields, Mark Gahegan, Michael Goodchild, Mary Hegarty, Kim Kastens, Alex Klippel, David O’Sullivan, Amy Shelton, Barbara Tversky, David Uttal

Phase 1: Moderator—Michael Goodchild; **Recorder**—Alex Klippel; **Reporter**—Amy Shelton
What do we know? What do we need to know? Framing the Research Agenda

This group began by reviewing **what we know now** about educating spatial thinking. The group agreed that there is general and broad evidence that spatial skills play an important role in STEM learning, that visual explanations improve comprehension, and that there are good examples of training spatial skills within disciplines. It is also clear that “one size does not fit all” and a heterogeneous set of skills that are applicable in different disciplines and situations were discussed.

Next the group considered **what we need to know** about educating spatial thinking. The group agreed that a taxonomy of spatial skills is required, in which we identify the general categories and types of spatial skills, the skills that are relevant to different disciplines, and which skills are common across disciplines that might be general problem-solving skills.

The group spent some time considering the uses of visualization, as a tool for problem solving, for comprehension and learning, and as a tool for discovery. The uses of tools, such as visualization may differ across levels of education as well as disciplines and we must better understand how to foster their use.

Another important issue identified by the group was when and where spatial skills transfer. Successful implementation of training spatial skills depends on teaching the skills in a way that they will transfer beyond specific courses to other courses and disciplines and, hopefully, into future life skills. Cognitive science research has indicated that transfer of training is rare and difficult to achieve; how does this apply to the more specific cases of spatial skills?

Finally, the discussion focused on **making the case** for spatial education across the curriculum. The group focused on the fact that students are currently much more engaged in “visual media” than in the past. Research is needed to identify what types of visualization and spatial problems they are encountering, and what students know coming into college. Do they have more exposure to the kinds of visualizations that we think are important? Are these visualizations effective for comprehension? That is, are students’ prior experiences fostering the skills we want to develop?

The group considered that demonstrations of effectiveness of spatial education are necessary to **make the case** for spatial thinking. This could partially involve revisiting discipline-specific skills, but we must cast a broader net than discipline-specific assessments. The group also questioned the focus on STEM disciplines, specifically, and the need to define the breadth of our focus—which in turn will shape the goals of the educational approach and assessments. Another issue is whether assessments must be put in place before training, or if it is effective to go ahead and train now.

Final issues addressed by the group were cross cultural exploration and the role of self-efficacy (i.e., self-confidence related to spatial skills).

Phase 2: Moderator—William Bechtel; **Recorder**—Billy Fields; **Reporter**—David O’Sullivan
Framing an Undergraduate Course Syllabi and / or Program Curriculum

The general conclusion from this group is that we currently need a grassroots approach for training in spatial thinking. That is, we are not ready for a “Decade of Thinking Spatially (DOTS, although it would be nice to say we could “join the DOTS”)! The group felt that at this stage, consortia and multipronged approaches to teaching spatial thinking were best, and the approaches might include micro-insertions in courses, general education classes, spatial minors, and sets of courses that teach job skills, etc. This multipronged approach was referred to as “a quiet revolution.”

The group also listed justifications for spatial thinking curricula: **1)** spatial curricula help develop workforce skills; **2)** our current nature is a “visual culture”; and **3)** consideration of problems facing humanity at this time (resource distribution, global warming). The point was made that these are complex spatial problems and might be best met by students who are trained as spatial problem solvers. Further, it can be argued that spatial thinking tools enable us to solve important problems facing humanity. However, it is also important to acknowledge that problem solving will not work as justification in the humanities, where we might emphasize the fact that spatial thinking helps students “ask questions in different ways.”

In terms of the specifics of a spatial-thinking curriculum, the group spent some time exploring how to “spatialize” courses with micro-insertions, etc. This is a challenge in our current “silo culture” in which we have many different vocabularies for space across the different disciplines. One possibility is to pick spatial concepts (e.g., “dispersion”) that could be addressed in different courses (e.g., dispersion of molecules in a chemistry class, dispersion of animal species in ecology, spread of ideas in a history class, and so forth). An idea was to pick a “concept of the year” for a campus, and give professors some incentive to include a discussion of this concept in their courses (some felt that that had been tried before). Another approach was to teach a freshman seminar with a deliberate blend of disciplines that force the abstraction of basic concepts. Other examples of basic concepts discussed included spatial dependence, spatial heterogeneity, networks, and hierarchies.

The group also discussed issues that arise in a GE course, such as not being able to rely on students having basic skills (e.g., GIS, Illustrator) and having to fit the course into specific general education areas defined by a campus (for example, the spatial thinking GE course at Harvard was in the mathematical reasoning area and was criticized for not being mathematical enough).

GIS as a job skill was discussed as another place to start, however, teaching GIS requires multiple courses and it cannot be done in a single GE course. The group also questioned whether GIS alone is what should be taught, or whether there is a broader set of skills to be addressed beyond GIS (e.g., data visualization was suggested).

Finally, the group acknowledged that different spatial skills are necessary for different disciplines. For example 3D spatial skills are relevant for science, engineering, and architecture, whereas 2D geospatial notions are more relevant in the social sciences and humanities. Just as we cannot just teach GIS, we also cannot use STEM learning as the sole justification for a spatial thinking curriculum.

General Discussion of Breakout Reports

The general discussion focused on four issues: **1)** claiming value in training spatial thinkers; **2)** assessing the role of visualization in spatial thinking; **3)** maintaining balance with technological changes; and **4)** determining what can and should be done to advance spatial reasoning in undergraduate education.

Making the case for the value of training in spatial thinking can draw on findings related to students performing better in STEM disciplines if they have strong spatial skills (N. Newcombe, S. Sorby), but the case can also be framed around enhancing student capabilities as problem solvers (Sinton), as communicators (R. Mayer), and as collaborators (B. Tversky). Greater attention must be placed on supplementing verbal communication with visual communication and using diagrams to share information in group efforts. The value of spatial training might also be addressed by assessing the consequences of doing nothing to improve society's spatial reasoning skills.

The extent to which visualization is central to spatial thinking was a source of contention, with the claim that spatial thinking goes beyond visualization and that too much attention to the visual may be limiting (D. Montello). Other modes of communication that create spatial cognition include sound and haptic experience (W. Kuhn). Nonetheless, the growing abundance of diagrams, maps, and other graphics have increased human reliance on the visual and we must devote more attention to improving general competency (B. Tversky, M. Hegarty) and verifying whether or not consumers face difficulties (S. Slater) in the interpretation of scientific and general media visualizations.

In the past 20 years, technology has made a vast difference in the scale, speed, and capacity to create and disseminate spatial visualizations. What was once a time-consuming craft industry is now managed by computers and other technologies (R. Downs). Now we confront the need to keep up with the technical developments and, in many cases, to maintain spatial abilities in the face of tools (e.g., GPS) that perform tasks for us automatically (e.g., navigate through space) (S. Sorby). Even though the media now produce a profusion of detailed maps (including highly sophisticated electoral maps [P. Bol]), it is questionable that the population is educated to understand the nuances and consequences of how data are represented on maps (D. Janelle). Technology is replacing spatial thinking when students push a button to produce a buffer zone on a map (D. Montello). Although the ease of pressing the button for quick visualizations may allow more time for other kinds of analyses (B. Tversky), it was argued that students must be trained to know what they are doing, as well as understand the rationale for a buffer display and the consequences of varying its parameters (K. Janowicz).

Putting into action some of the ideas of this meeting means developing concrete plans to make the case for how enhanced spatial literacy will make students better problem solvers and communicators, but we must also be prepared to evaluate the results (N. Newcombe). We can benefit from this meeting by using it to seed and support broader discussions (blogs) and to identify resources that will help with implementations on a broad national scale. With modest infrastructure and the dedicated commitment of a few scholars across different disciplines, campuses can build on existing activities to create a home for spatial thinking in the academy (M. Goodchild, D. Janelle).

Wrap-up and Synthesis

Five participants were asked to review the proceeds of the entire meeting to help identify key take-away observations, summarize the meeting's findings, point to directions for further work, and suggest follow-up initiatives.

David Bodenhamer, Indiana University Purdue University, Indianapolis

Seven key questions/observations arise from this meeting:

- 1) We are at an interesting cultural moment, aware of how global the world is, YET keenly aware of the local differences that separate us. Digital technology allows us to navigate these complex realities and to visualize spaces and places. But, in doing so, what is our goal—spatial thinking? spatial literacy? spatial awareness? And, who is our audience? Students and administrators? Yes, but we've talked little about professors and external interests, and this may be where we can make a difference. If we don't know where we want to go, it doesn't matter what road we take.
- 2) We make things too complicated—we need to educate in the obvious, rather than illuminate the obscure. But, what is the essential? What has value? And to whom? How do we make the obvious visible?
- 3) For the humanist, the obvious is not space, it is place. Place is lived space, the space we have claimed by our presence, our memories, and our conflicts. How do we take this abstraction of space and make it relevant to the humanities?
- 4) Maps are powerful and familiar, whether physical, cognitive, or conceptual. Mapping data can provoke conversations and elicit interpretations in solving problems.
- 5) What is missing for the humanist is time. Mappings based on volunteered geographic information (VGI), neogeography, and naive geography have provided some success in linking time with space and in addressing the more nuanced interpretations of place. But how do they fit into a research-and-teaching agenda on spatial thinking?
- 6) Vision is important and must be clear and strategically opportunistic to find leverage points (e.g., collaborations and civic engagement) where we can be successful.
- 7) Take actions that are consistent with the vision. Within our institutions, use teaching, research, and civic engagement as opportunities to demonstrate the power of spatial thinking; teach by doing—create projects that allow students to experience how we think about and analyze space; seek multiple points of entry that are institutionally and culturally sensitive to different perspectives and practices; develop a common language and use it to tell stories about why spatial thinking is important; and find ways to embed a critical spatial intelligence into our tools.

David H. Uttal, Northwestern University

The design disciplines, history, and the humanities may provide better examples for STEM-oriented research in spatial learning than traditional STEM disciplines. What we don't know is why spatial thinking is used in different contexts—we may need discipline-based ethnographies

of spatial thinking. Hence, a case can be made for discipline diving to identify and assess domain-specific spatial skills.

Attention to transferrable skills is especially important. Mathematics and language are demonstrably transferrable, and space could be more like reading and math. Although we don't know a lot about spatial learning, there is transfer. A key idea is to market what we are doing. For example, tie research on spatial learning to science standards, providing arguments and evidence of how it improves reasoning. While we may foresee big plans to advance the role of spatial cognition in the curriculum, a strategy to implement it incrementally may be most useful. Attention to developing effective measures must go beyond achievement and psychometric test scores (mental rotation and memorization) to recognize the importance of "Habit of Mind." An NSF project on promoting spatial problem solving in geospatial learning (with R. Kolvoord, James Madison University) was cited as an attempt to move in this direction.

Werner Kuhn, University of Münster

Kuhn presents seven take-away points and links them to research needs:

- 1) Integrate concepts and skills—concepts to organize skills and skills operationalize concepts.
- 2) Move beyond STEM to determine what specific abstraction and communication skills benefit from spatial thinking, what problem-solving strategies are spatial (e.g., G. Pólya), and what skills employers are seeking.
- 3) Considering statistics as a meta-science, determine if there is a parallel between "statistical thinking" and spatial thinking and identify the kind of data that should be the foundation of spatial thinking and spatial learning.
- 4) Since spatial concepts such as distance and scale are moldable to fit different purposes, we need to profile them for different knowledge domains and applications and to formalize/map profiles through ontologies.
- 5) Demonstrate how spatial thinking simplifies problem-solving, using simpler spatial technologies than GIS.
- 6) Adopt an outward-looking perspective to GIScience that communicates that GIScience is *the* spatial information science, yet recognizes the needs for distinct spatial theory within different domain problems.
- 7) The incorporation of spatial thinking across the curriculum calls for a global effort to determine what is universal to spatial studies programs. While recognizing that different implementation approaches will be required in different countries, can we work together globally on a MOOC?

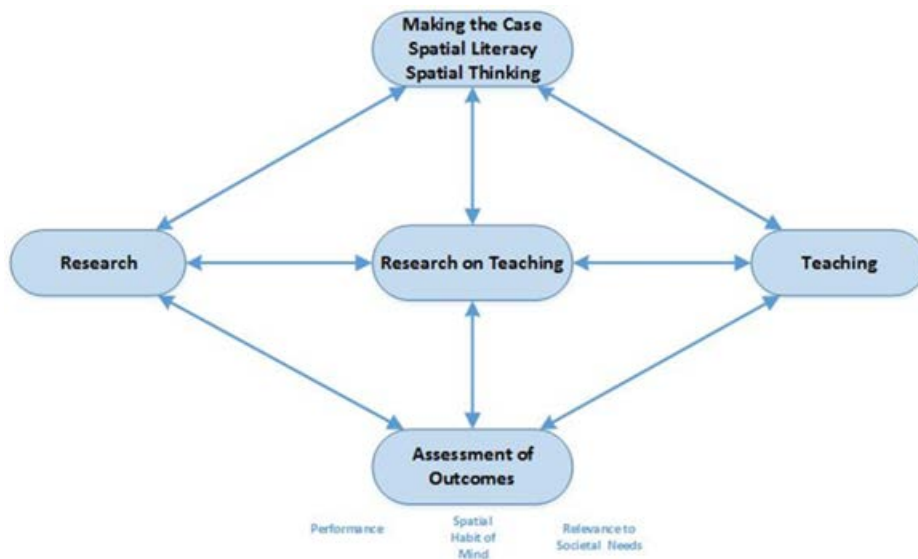
Krzysztof Janowicz, UCSB

More attention is needed to distinguish domain-specific spatial abilities from domain-independent abilities. For example, in geography we must devise ways of testing how people think about core spatial concepts (e.g., scale, spatial heterogeneity, analogs, distances, and topology). Yet, abilities to use these concepts are not assessed by current focus on cross-domain

spatial abilities such as mental rotation and spatial perspective. There is also a need to “make space for time.” Seeing places as a sequence of events enables the understanding of processes. Space and time are fundamental to the organization of knowledge and, as such, we can exploit this to illustrate how spatial thinking can reduce error in judgments and solve problems. This could be the focus for using micro insertions in text and for teaching to illustrate the value of spatial thinking in various knowledge domains.

Barbara Tversky, Columbia Teachers College

Spatialization needs to focus on appropriate abstraction. In comparison to language (with its attention to phonetics, semantics, syntax, etc.), space and its representations have their own structures of objects, relationships, and meanings. A piecemeal approach to acquiring spatial skills may not make students better at understanding and drawing inferences. There is need for a holistic approach through creative thinking and the integration of visual descriptions, explanations, and narratives. Citing work by Bobek and Tversky, visual explanations facilitate learning more effectively than written explanations and visual representations encourage inference from structure to function with greater attention to space-time patterns and applications of cross-cutting concepts (e.g., networks/trees; timelines/decision trees; boundaries; diagramming; diffusion and dispersion, etc.) to explore ideas and relationships.



Concluding Observations and Recommendations

More than 40 participant position papers and nearly two-dozen presentations, and notes from discussions in Santa Barbara, all available at <http://www.spatial.ucsb.edu/events/STATCC/participants.php>, have been reviewed to identify key observations and recommendations. As Tim Shipley noted, it is likely that, as a result of this meeting, participants have changed their conceptions about the nature of spatial thinking and about the possibilities for its incorporation in the curriculum. This section of the report complements the “Summary of Primary Findings and Outstanding Issues” and addresses the specific “Questions for Consideration” that were introduced in the Executive Summary and Introduction.

What are best current practices in spatial education at the college level?

- A variety of approaches are currently being taken at different universities and colleges, including: general education classes, spatial minors, freshman seminars, micro-infusions of spatial thinking modules in different courses, and focused courses on spatial skills for specific disciplines (e.g., engineering). The examples of minors and general education courses presented at the meeting are exportable and could be adapted for use at many other institutions. The value of alternative strategies and practices (e.g., course requirements for minors) also provides test cases for research evaluation.
- The development of a MOOC (massive open online course) on spatial thinking offers considerable potential for dissemination on a broad and global scale (a number of meeting participants convened an evening session to review this possibility). The idea of engaging students from a diverse set of countries and cultures presents opportunities for research on the assessment of spatial thinking in a variety of meaningful contexts.
- There was consensus that a variety of approaches should continue to be taken. Although we are far from knowing what approaches are most effective, this should not stop us from adopting a grass-roots approach to developing instruction in spatial thinking where we can, depending on the resources and opportunities available at different institutions.

What role do technologies, such as geographic information systems and virtual environment technologies, play in developing spatial thinking skills?

- GIS is a powerful technology that is currently applied to many disciplines across the college curriculum. GIS has had significant impact on the environmental sciences and in various areas of resource management in the professions, government, and industry. In recent years, it has expanded its research presence into the social and health sciences, and is a technology of growing interest in the humanities. Nonetheless, historians (and even geo-information scientists) rightly complain of its inability to treat time in a transparent way to accommodate sequences of change and representations of time-space trajectories. The rapid accretion of new functions within its menu structures has led to non-intuitive procedures that impede learning. The creation of a more streamlined organizational structure for its many tools and functions could provide research opportunities for aligning GIS with a theoretically and ontologically grounded set of spatial concepts and

procedures to solve a variety of problems. Enhanced intuitive order within a GIS offers the prospect of its greater integration within the curriculum and as a tool for analysis, problem solving, and communication.

- For purposes of supporting spatial thinking across the curriculum, GIS is not the only relevant technology. For example, it currently has very little applicability in physical sciences, such as physics and chemistry, or in many branches of engineering, where more general visualization technologies are of greater relevance, including the creation and effective use of graphs and diagrams.
- This meeting gave only limited attention to the educational value of animations, interactive visualizations, and virtual environments. These are areas of continued development, in computer science and in the arts and media-oriented disciplines/professions. There is a significant need to integrate these developments into the framework of general spatial thinking and skill development.

Can we identify a set of general spatial skills that are relevant to spatial thinking across several disciplines?

- Much work needs to be done to develop a common understanding and language for characterizing what is domain-general and what is domain-specific in spatial thinking. We need precise definitions of terms such as “spatial skills” and “spatial concepts,” and a common language for referring to aspects of spatial thinking.
- Representation is a common theme across many disciplines. One set of skills that might be taught in a domain-general way are skills for representing information, and for critiquing and interpreting representations. It is our assessment that the idea of embedding critical spatial thinking at all levels of education is gaining traction but needs far more attention and evaluation.
- There are common concepts that appear to span many knowledge domains (e.g., a spatialized frame of reference, scale, movement, dispersion, spatial dependence, and spatial heterogeneity). But, in contrast, many concepts and skills are specific to particular disciplines or groups of disciplines. For example, mental rotation is an important spatial skill in the arts and in chemistry, geology, and engineering, but considerably less relevant to spatial thinking in the social sciences. Understanding gesture as a means of communication may have more universal application.

Are spatial skills best trained in the context of a discipline or in a domain of general knowledge? 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?

- We have limited evidence that training of spatial skills (such as mental rotation) can enhance science learning, but we do not know the answer to this question.
- The issue of transfer is critical. Cognitive and educational studies have shown that transfer of skills beyond the context in which they were taught is extremely difficult to produce. It is, therefore, important to consider how to teach spatial thinking skills such

that they transfer to a range of situations. For now, even evidence that we can successfully train spatial skills in the context of a discipline is valuable.

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?

- “One size does not fit all” and spatial thinking skills mean different things for different disciplines. While geography and geometry may support spatial thinking skills, they do not support all of the spatial thinking skills that are relevant across the college curriculum. For example, geography deals primarily with 2D (or 2½D processes) at the scale of the earth. Sciences such as chemistry and astronomy examine 3D processes at much smaller and larger scales.

What are learning outcomes for spatial thinking curricula, and what form should assessment take?

- Although we have good assessments for very specific spatial skills (e.g., mental rotation), there is a critical need to develop much broader assessments of a range of both domain-general and domain-specific spatial proficiencies.
- Good assessments depend on having a better understanding of what we mean by spatial thinking. For example, how might we measure “a spatial habit of mind?” And, can we develop assessments based on more complex space-time systems of integrated concepts in contrast to measures of single concept measures of competency?

What are the administrative challenges and opportunities for implementing spatial thinking courses and programs at the college level?

- Spatial thinking is fundamentally cross disciplinary. Although this poses difficulties in the current “silo culture” of the academy, interest in cross-/trans-disciplinary research and teaching appears to be of growing interest. Mathematics Across the Curriculum (Dartmouth College), Foreign Languages Across the Curriculum (St. Olaf College), and Spreadsheets Across the Curriculum (University of South Florida) were cited as parallel examples to our focus on Spatial Thinking Across the College Curriculum.
- In making the case for space, our proposals will be competing for the attention of top administrators against other worthy initiatives (e.g., the “critical thinking” movement, or “media literacy”). However, it may be possible to collaborate in aligning spatial thinking with these alternative initiatives (e.g., critical spatial thinking), and such a pairing may not only be strategic but appropriate and desirable.
- In addition to focusing on curriculum innovations, we might also consider ways of incorporating spatial thinking within professional development programs for college faculty.
- Building collaborations around a consortium of schools that are in physical proximity (e.g., in Southern California, UCSB, USC, Redlands, and Southwestern Community College) may offer opportunities to achieve a critical mass of resources and talent to

address spatial literacy needs in different institutional settings. This would also provide a useful context for comparative research and assessment.

- Arguing the case for space before appropriate committees and study groups within discipline-based associations would provide additional leverage for curriculum changes.
- Finally, we must gather qualitative and quantitative data from students who participate in different spatial thinking programs. Information about their career paths may provide evidence for any advantages that a spatial education gives to students in their future studies and in the global job market. Evidence of their having developed a spatial “habit of mind” may need to come from a variety of measures, some which have yet to be created.

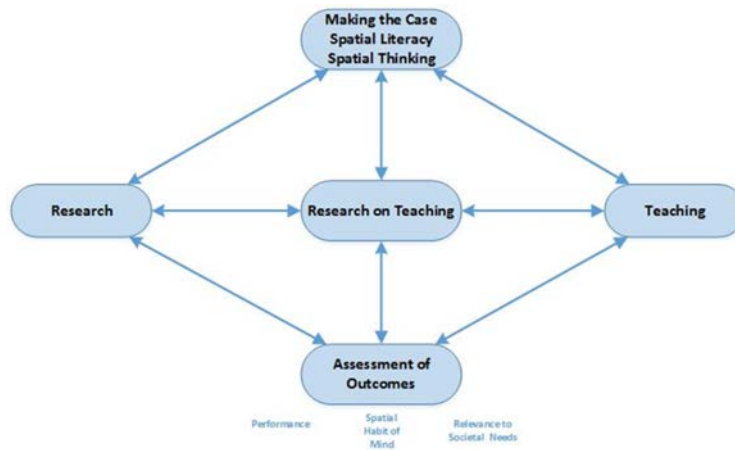
What opportunities are there for substantive support for academic initiatives in spatial thinking?

- Public research funding agencies have been the primary source of support for programs that enhance spatial analysis and spatial learning.
- NIH has only recently supported workshops on spatial analytical methods for population and health research and is currently seeking to coordinate spatial interest across a range of its institutes.
- NSF has a long tradition of support for spatial perspectives in the sciences but its initiatives are fragmented. For instance, the “geography and spatial sciences” program is concerned with space but has a divided focus. Programs concerned with education and learning science have also been instrumental in the support of research and instructional development. Copies of this report or a related white paper would be of likely interest to NSF program officers. A visit to NSF by a small group of meeting participants to give a colloquium might benefit the NSF community.
- Digital humanities are interested in visualizing flows/movement, and there are opportunities for supporting such initiatives through the National Endowment for the Humanities.
- Private foundations also play a critical role in support of innovative education and research programs, including sponsorship of workshops and conferences. Organizations mentioned include the Mellon Foundation, the Keck Foundation, and the Teagle Foundation.
- Papers in *Science* and *The Chronicle for Higher Education* could have broad and significant impact.

In Summary

To make **the case for space, basic research** must come to a more fundamental understanding of what we mean by spatial thinking, including different varieties of spatial thinking across the college curriculum, and identifying what is common to spatial thinking across disciplines. At the same time we must continue to develop methods of **teaching** spatial thinking where we can and with the current resources. Further, we need **research on teaching** spatial thinking, including

assessments of what is learned from programs that aim to teach spatial thinking. We must also **document and demonstrate** where and how spatial thinking prepares students for academic success and allows them to better compete in the job market and global economy.





Agenda
SPATIAL THINKING
ACROSS THE COLLEGE CURRICULUM
December 10–11, 2012
Upham Hotel, Santa Barbara

SUNDAY DEC 9: ARRIVAL DAY

Participants arriving throughout the day

Meet in the Upham lobby at 6:00 p.m. if interested in forming groups for dinner

MONDAY, DEC 10: DAY 1

- 8:15 am Welcome and Introductions
8:30 **Overview of Goals:** Mary Hegarty, UCSB
- 8:45 am** **SESSION 1: Defining the Need for Spatial Learning**
Moderator: Mary Hegarty
- 8:50 Roger Downs, The Pennsylvania State University
9:10 Nora Newcombe, Temple University
9:30 **Discussant:** Kim Kastens, Education Development Center
9:45 Open discussion
10:15 am *Break*
- 10:35 am** **SESSION 2: Challenges of Spatial Thinking across the Disciplines**
Moderator: Tim Shipley, Temple University
- 10:40 Lynn Liben, Pennsylvania State University [STEM learning perspective]
11:00 Peter Bol, Harvard University [Humanities perspective]
11:20 Michael Goodchild, UCSB [GIScience perspective]
11:40 **Discussant:** Karl Grossner, Stanford University
12:00 Brief open discussion
12:10 pm *Lunch, Louie's, served in the garden, Upham Hotel*
1:10 Demo: *Getting Started with Web GIS*; Tom Baker and David DiBiase
- 1:30 pm** **SESSION 3: The Challenges: Spatial Thinking within Disciplines**
Moderator: Don Janelle, UCSB
- 1:35 David DiBiase, Esri—GIScience
1:50 David Tulloch, Rutgers University—Architecture/Landscape Architecture
2:05 Stephanie Slater, Center for Astronomy & Physics Education Research—Astronomy
2:20 Mike Stieff, University of Illinois, Chicago—Chemistry
2:35 **Discussant:** Mark Gahegan, University of Auckland
2:50 Open Discussion
3:05 pm *Break*
- 3:25 pm** **SESSION 4: Models of Curriculum Development for Spatial Thinking Across the College Curriculum**

- Moderator:** Diana Sinton, University of Redlands
3:30 Wesley Bernardini, University of Redlands
3:40 Sheryl Sorby, The Ohio State University
3:50 Don Janelle, UCSB
4:00 John Wilson, University of Southern California
4:10 Ken Yanow, Southwestern College and the National Geospatial Technology Center of Excellence
4:20 Open Discussion
4:40 pm *Wine and Cheese reception, Upham Hotel lobby (discussions to continue; demos in the Garden and Sun rooms)*
- Demos** (all demos will be given from personal computers with no projector access):
- *The iOS Spatial Cognition App*; Scott Bell
 - *The Spatial Thinking Module for Maps and Spatial Reasoning*; Keith Clarke
 - *Assessing Spatial Thinking using Category Construction Tasks*; Alexander Klippel
 - *A Showcase of Spatial Thinking in Undergraduate Research*; Sarah Kriz
 - *Ori-Gami—Orientation Gaming for Kids*; Werner Kuhn and Thomas Bartoschek
 - *Spatial Simulation: Exploring Pattern and Process*; David O’Sullivan
 - *A Virtual Reality System for Studying Representational Competences in Chemistry*; Andrew Stull
- 6:00 pm *Convene in Lobby for walk to Opal Restaurant*
6:15–8:15 pm *Dinner (group event, Opal Restaurant)*

TUESDAY DEC 11 DAY 2

- 6:00–8:30 am *Mission Canyon Hike (optional)*
- 9:15 am **Quick review of the day’s objectives**
- 9:25 am Breakout Phase 1—What do we know? What do we need to know? Framing the Research Agenda**
- Group 1— **Moderator:** Laura Carlson; **Recorder:** John Pani; **Reporter:** Scott Bell
 - Group 2— **Moderator:** Stephen Hirtle; **Recorder:** Sarah Perez-Kriz; **Reporter:** Dan Montello
 - Group 3— **Moderator:** Michael Goodchild; **Recorder:** Alex Klippel; **Reporter:** Amy Shelton
- 10:55 am *Break*
- 11:15 am Breakout Phase 2—Framing an Undergraduate Course Syllabi and / or Program Curriculum**
- Group 1— **Moderator:** Eric Fournier; **Recorder:** Robert Kolvoord; **Reporter:** Beth Casey

- Group 2— **Moderator:** Diana Sinton; **Recorder:** Karl Grossner; **Reporter:** Fiona Goodchild
- Group 3— **Moderator:** William Bechtel; **Recorder:** Billy Fields; **Reporter:** David O’Sullivan

12:15 pm *Box Lunch, Upham Hotel—Continue Phase 2 working through lunch*

12:45 pm *Break while Recorders and Reporters meet to prepare presentations*

1:30 pm **Reports from breakouts** on Phase 1 and Phase 2 questions (10 minutes for each report)

2:30 pm Plenary discussion

3:00 pm *Break*

3:20 pm **Plenary discussion of next steps**

Moderator: Tim Shipley

Summary Wrap-up Presentations (what are the take-away points from this meeting?):

- David Bodenhamer, Indiana University Purdue University, Indianapolis
- David Uttal, Northwestern University
- Werner Kuhn, University of Münster
- Krzysztof Janowicz, UCSB
- Barbara Tversky, Columbia Teachers College

4:40pm **Open Discussion on Planned Initiatives**

Closing remarks: Nora Newcombe and Mary Hegarty

Wine and cheese in the Lobby

Evening *Dinner on your own in Santa Barbara*

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Specialist Meeting Position Papers
Spatial Thinking Across the College Curriculum

Santa Barbara, CA

December 10–11, 2012

Copies of these papers are available at

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

Thomas R. Baker, Advancing STEM Education, GIS and Spatial Thinking
Esri

William Bechtel, Inventing and Learning from Novel Diagrammatic Procedures
University of California, San Diego

Scott Bell, Spatial Thinking: Learning Outcomes and Spatial Meta-Concepts
University of Saskatchewan

Wesley Bernardini, Developing a Spatial Minor at the University of Redlands
University of Redlands

David Bodenhamer, Humanities and Spatial Literacy/Spatial Thinking
Purdue University, Indianapolis

Peter K. Bol, Spatial Thinking and Spatial Technologies in History and the Humanities
Harvard University

Laura Carlson, Spatial Thinking and Reasoning Across the College Curriculum
University of Notre Dame

Beth Casey, What are Learning Outcomes for Spatial Thinking Curricula: What Form should Assessment Take?
Boston College

David DiBiase, Implementing Spatial Thinking Across the College Curriculum
Esri

Roger M. Downs, Making a Place for Space
The Pennsylvania State University

Billy Fields, Enhancing Spatial Thinking in Public Administration and Policy
Texas State University

Eric J. Fournier, Infusing Spatial Thinking Across the Disciplines: A Faculty Development Perspective
Samford University

Mark Gahegan, How is Space Represented and Analyzed by Scientific Disciplines Other than Geography
University of Auckland, New Zealand

Fiona M. Goodchild, How Does Spatial Thinking Contribute to the NRC Framework for K-12 Science Education?
University of California, Santa Barbara

Michael F. Goodchild, A GIScience Perspective on Spatial Thinking Across the Curriculum
University of California, Santa Barbara

Karl Grossner, Concepts and Principles for Spatial Literacy
Stanford University Libraries

Mary Hegarty, Broadening Education in Spatial Thinking
University of California, Santa Barbara

Stephen C. Hirtle, Cognitive Mapping and Spatial Thinking
University of Pittsburgh

Donald G. Janelle, Building Support Systems for Spatial Literacy
University of California, Santa Barbara

Krzysztof Janowicz, Giving Order by Space and Time
University of California, Santa Barbara

Kim Kastens, Transitioning into a Data-savy Adult
Education Development Center (EDC)

Alexander Klippel, The Challenge of the Medium
The Pennsylvania State University

Robert Kolvoord, Spatial Thinking Across the College Curriculum
James Madison University

Werner Kuhn and **Thomas Bartoschek**, Spatialization before Specialization
University of Münster

Lynn S. Liben, Spatial Education Across the College Curriculum: A Psychologist's Perspective
The Pennsylvania State University

Richard E. Mayer, Spatial Thinking and the College Curriculum
University of California, Santa Barbara

Daniel R. Montello, Spatial Thinking Across the College Curriculum
University of California, Santa Barbara

Nora S. Newcombe, Spatial Thinking Across the College Curriculum
Temple University

David O'Sullivan, Spatial Thinking in Undergraduate Research
University of Auckland, New Zealand

John R. Pani, Designing Better Methods of Instruction in Spatial Domains
University of Louisville

Sarah Perez-Kriz, Spatial Thinking in Undergraduate Research
University of San Diego

Amy Lynn Shelton, Spatial Thinking and Reasoning Across the Curriculum
Johns Hopkins University

Thomas F. Shipley, Challenges to Integrating Spatial Thinking in the College Curriculum
Temple University

Diana Sinton, Spatial Thinking Across the College Curriculum
University of Redlands

Stephanie J. Slater, Transforming Learning in Astro 101: Using Spatial Curricula to Teach Spatial Concepts
University of Wyoming

Sheryl A. Sorby, Spatial Skills Training to Improve Student Success in Engineering
Michigan Technological University

Mike Stieff, Spatial Thinking Across the College Curriculum
University of Illinois, Chicago

Julie Sweetkind-Singer, Spatial Thinking Across the College Curriculum
Stanford University

David Tulloch, A Design Perspective on Spatial Thinking
Rutgers University

Barbara Tversky, Spatial Thinking
Columbia Teachers College

David H. Uttal, Envisioning the Spatial Curriculum: A Research Agenda
Northwestern University

John P. Wilson, Cultivating Spatial Intelligence
University of Southern California

Ken Yanow, Perspective on Spatial Thinking Across the College Curriculum
Southwestern College