12 Concepts and Principles for Spatial Literacy

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Spatial thinking capability is strongly correlated with educational and professional performance in science, technology, engineering, and mathematics (STEM) fields (Shea, Lubinski, and Benbow 2001; Uttal and Cohen 2012; Wai, Lubinski, and Benbow 2009; Webb, Lubinski, and Benbow 2007), but the systematic and integrative instruction of spatial concepts, principles, and reasoning skills is not an explicit goal in K–12 or college curricula. Spatiality also is ubiquitous in many humanities fields, including history and fine arts. Although educators do set standards for verbal literacy, numeracy, and analytical reasoning, there has been no comparable articulation of what it means to be spatially literate. That said, the 2006 National Research Council report *Learning to Think Spatially* did outline high-level "components of spatial literacy" (NRC 2006, pp. 16–20) that are a useful starting point. To paraphrase: A spatially literate person has (1) good knowledge of fundamental spatial concepts, (2) "spatial ways of thinking and acting"—that is, the "habit of mind" to think spatially and to apply spatial methodologies to solve problems, and (3) proficiency in the use of spatial tools and technologies. From this we derive a concise working definition of spatial literacy for this chapter: an understanding of fundamental spatial concepts and principles and the capability to recognize their appropriate application in answering scientific, engineering, and humanistic questions, aided by spatial technologies.

This chapter primarily addresses spatial conceptual knowledge. After summarizing our recent efforts to enumerate spatial concepts, we outline a prospective college-level course that entails applications of spatial concepts and related principles. Although many spatial concepts and principles are highly general, they are typically specialized distinctively in individual disciplines. Important complementary studies of such specializations are being undertaken by cognitive psychologists and education researchers working with interested professionals from several fields—most notably the geosciences, geography, and chemistry (Hegarty, Stieff, and Dixon 2013; Jo and Bednarz 2009; Manduca and Kastens 2012)—a practice we term *discipline-diving*. In this chapter, drawing on discipline-specific concepts and principles (the likely pragmatic source for defining spatial learning objectives for course modules and lesson plans), we frame an initial course outline to enhance spatial literacy across the undergraduate curriculum.

Given the reality of finite "curricular space," we recognize the difficulties of introducing a new course at any educational level. Correspondingly, the proposed course and related discussion are intended to raise awareness of spatial literacy among educators; it is a thought experiment that presents an answer to the question "What should a spatially literate person know?" In instances where an entirely new course or course module is not feasible, the outline may suggest the insertion of simple examples that expand on concepts and on the articulation of problems to contribute spatial perspectives that enhance parts of existing courses. (See Hegarty et al. 2013.)

Perhaps it is the ubiquity of spatiality that prevents us from viewing spatial reasoning as a distinct practice, as we do mathematics, reading, and writing. Yet the 2006 NRC report presents the case for regarding spatial thinking as a distinct complement to the three Rs. (See Hegarty 2010 for a discussion of "spatial intelligence.") The report documents how we think *in* space, *about* space, and *with* space. We think *in* space as we navigate through buildings and cityscapes, play sports, dance, or organize storage shelves. We think *about* space when analyzing the structure, function, motion, and distribution of things in the world, at scales from nano to cosmic—whether seeking scientific explanations for natural phenomena or designing a tool, a building, or a dam. We think *with* space when we create or interpret diagrams and maps, or reason by spatial metaphor—a powerful and commonplace cognitive strategy (Lakoff and Johnson 1980).

Thinking in, thinking about, and thinking with space are expressed differently depending on the conceptual foundations and methodologies associated with disciplines and professional pursuits. General spatial literacy does not entail the specialized spatial approaches and levels of expertise required for careers as surgeons, geologists, architects, or fighter pilots. We are not all gifted writers or mathematicians, but nearly everyone can become sufficiently proficient at reading, writing, and manipulating numbers to be an informed and fulfilled citizen. Similarly, we maintain that general spatial literacy is within reach of nearly everyone, will enhance skills for problem solving in careers and in daily life, and should be a goal of basic education.

Locating Spatial Concepts

One of the foundations of spatial literacy is the ability to reason with and to apply spatial concepts. Our efforts in nurturing such capabilities have focused on the support of spatial teaching and learning at the college level. In the sections that follow, we first describe research initiatives to identify the spatial concepts used in different fields (Grossner 2012), then present a preliminary framework for organizing those concepts, and finally describe the development of a semi-automated mapping of concepts to enable the discovery of teaching resources cataloged in the National Science Digital Library.

Mining existing spatial taxonomies

We examined twenty articles and books in which authors from eight disciplines discuss the centrality of spatial thinking in their fields and attempt to delineate fundamental spatial concepts (table 12.1). Some of these include an explicit taxonomy or schema of spatial concepts. For other authors and disciplines, important spatial concepts and concept relationships are extracted through content analysis of the text and section headings. The dominance of geography and psychology in the listing reflects disciplinary interests in, respectively, space as a primary dimension of analysis, and concepts, thinking and learning more generally. Although far less attention is paid to the role of spatial thinking in the literature of other

Table 12.1
Source documents on spatial concepts used in various disciplines.

Discipline	Source documents
Architecture and urban planning	Alexander 2004; Lynch 1984
Earth science	Kastens and Ishikawa 2006
Geography	DiBiase et al. 2008; Gersmehl 2005; Gersmehl and Gersmehl 2007; Golledge 1995; Golledge et al. 2008; Kaufman 2004; Marsh et al. 2007; de Smith et al. 2008; Nystuen 1963; O'Sullivan and Unwin 2002
Mathematics	Battista 2007
Linguistics	Johnson 1987
Psychology	Newcombe and Huttenlocher 2000; Piaget and Inhelder 1967; Tversky 2005
Science education	Mathewson 2005
Social science	Janelle and Goodchild 2011

Table 12.2
Categorized spatial concepts in TeachSpatial lexicon.

Category	Spatial concepts
Spatial structures	object, field, surface, network, region, area, place, neighborhood, landscape, zone, landmark, atom, cell, molecule, nucleus, conduit, coil
Spatial properties	composition, structure, size, shape, texture, mass, boundary, part, feature, center, layer, stratum
Space-time Context	space, space-time, location, environment, setting, site, situation, global, local, reference frame
Position	position, distance, direction, orientation
Spatial dynamics	motion, movement, dispersion, diffusion, transfer, transport, migration, explore, formation, destruction, grow, expand, diminish, merge, split, trajectory, wave, route, cycle, force, attract, repel, gravity, radiation, convection, absorb, release, erosion, eruption, flow, navigation, deformation
Spatial relations	adjacency, proximity, centrality, distribution, density, container, external, internal, spatial hierarchy, level, order, spatial organization, pattern, proportion, straight, symmetry, chirality, alignment, gradient
Spatial interaction	connection, link, bond, interaction, system, coordination, ecosystem
Spatial transformations	scale, rotation, projection, spatial integration, spatial interpolation
Representation	map, diagram, graph, cognitive map, representation, overlay, path, grid, coordinates, point, line, polygon, polyhedron, route perspective, survey perspective
Spatial principles	spatial autocorrelation, spatial heterogeneity, spatial association, distance decay, access, availability, isotropy, congruence

fields, this study (described more fully at teachspatial.org) seeks to make explicit their reliance on spatial principles and methodologies.

Although 185 concept terms were harvested from the sources listed in table 12.1, subsequent analysis pared the listing to 129 terms through removal of near-synonyms and redundancies. In turn, we grouped the terms into ten general categories (table 12.2). The 129 terms differ significantly with respect to complexity or level of abstraction and many have multiple definitions that often reflect disciplinary traditions. Furthermore, the positioning of terms within more general categories (although generally intuitively apparent) faces the inevitable ambiguity of terms that fit within multiple categories, leading to philosophical questions about the very nature of concepts. Two survey volumes on the topic (Margolis and

Laurence 1999; Murphy 2002) show that research has been almost universally limited to fairly simple exemplars—concepts as classes of things in the world, like birds and chairs—not especially helpful for more complex relationships associated with spatial concepts such as *neighborhood*, *connection*, and *structure*.

Measuring spatiality

We have adopted an extensional notion of what a concept is—mental constructs representing material and non-material entities, properties, and processes in the world, about which we communicate with language. Thus, concepts are comprised in part by the words and gestures used to communicate their intended meaning. For two perspectives on spatial gestures see the chapters by Malaia and Waller and the one by Atit, Shipley, and Tikoff.

In an experimental study, Grossner and Montello (2010) undertook to confirm whether the presence of spatial terms in scientific texts corresponded with human judgments of spatiality. First, they built a lexicon of 120 spatial terms from three sources: a distillation of the 185-term list mentioned above, salient terms in the topical headings of two spatial analysis textbooks, and a glossary of topological terms. They then assembled a corpus of 195,000 titles and abstracts of the National Science Foundation grant awards made by all NSF directorates and divisions between 1989 and 2009. A measure of "spatial-term density" for each award was generated using a computer program written to count occurrences of each term in each abstract document and, then, divide the sum of those counts by the number of words in the abstract. Per-document spatial-term-density values ranged from 0.00 to 0.61. For comparison with "'standard English,'" the same lexicon was used to rate the spatiality of other corpora, including 2,615 Wikipedia "featured" articles, the Academic subset of the Corpus of Contemporary American English (COCA), and course descriptions from seven schools within a major university (UNIV). The results are summarized in figure 12.1.

To help ground the spatial-term-density measure, Grossner and Montello conducted a survey that asked participants to rate the spatiality of twenty NSF abstracts, chosen to be representative of divisions across all eight directorates. The seventy respondents represented a sampling frame of (a) a university geography department's graduate students, faculty, and research staff, (b) individuals registered on the teachspatial.org website, and (c) members of the Spatial Intelligence and Learning Center's spatial network. This group is considered expert relative to the general population.

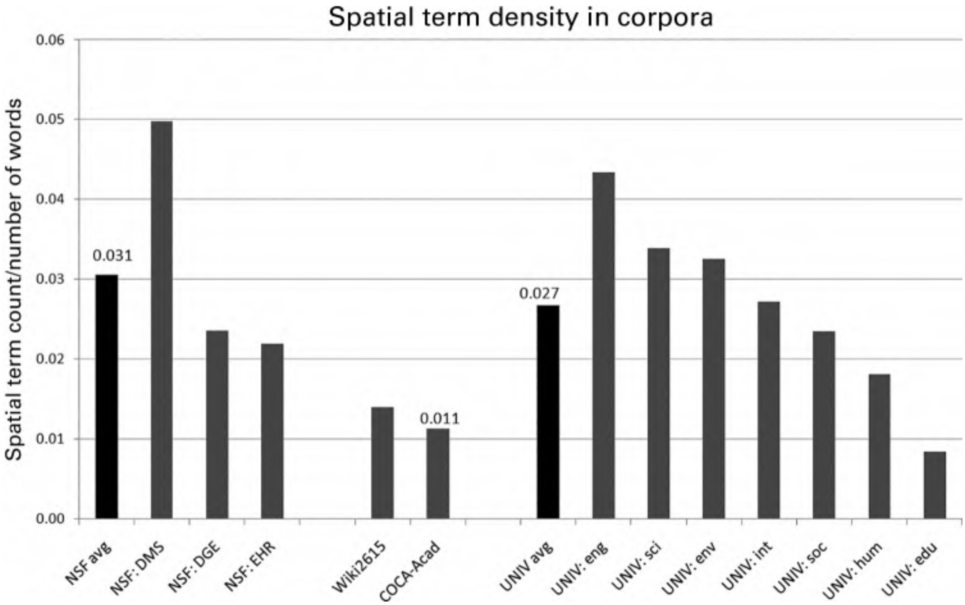

Figure 12.1
Spatial-term density in various corpora.

There was a rank correlation of 0.73 between the term-density measure and human judgments about the spatiality of the twenty abstracts. These results confirmed the value of using this method to search for spatiality in other texts, such as K–12 teaching standards and university course descriptions.

Locating spatial concepts in K–12 science standards

The next step in this investigation was to examine K–12 science teaching content standards to learn what spatial conceptual knowledge the average new college freshman might be expected to have. We convened a panel of eight "spatial experts" from the fields of science education, cognitive psychology, geography, and mathematics, and asked them to identify spatial concept terms present in each of the 150 National Science Education Standards for the subject areas of Physical, Life, and Earth and Space Sciences (NRC 1996), then subjectively rate each standard for its spatiality. We then rated the agreement among the eight spatial experts.

Each of the 150 NSES content standards was examined by four to six of the panel's experts and given a "spatiality rating" between 0 and 100. Averaged values indicated that Life Science was the least spatial of the three domains; that, although physics was seen as the most spatial, agreement among the experts varied more than for life and earth sciences; and that agreement among experts was greatest for standards judged as "very spatial" and "not very spatial."

In reading the NSES content standards, panelists highlighted all terms in the text that they judged to be spatial. Almost all of the spatial concept terms from table 12.2 were tagged when encountered, but many other terms were also deemed markers for spatial conceptual content in the standards—examples include 'earth', 'absorption', 'proportion', 'erosion', and 'coordination'. After rating and tagging standards, the group was asked what factors led to considering a standard as highly spatial. The following responses indicate the range of considerations. A standard can be considered highly spatial if

spatial reasoning methods are essential to understanding it,
it concerns relationships among objects either directly involving or bringing to mind distance, hierarchies, networks, structure (e.g., containment, or parts), or patterns,
it concerns observable components for which we can develop either mental or physical (graphic) spatial imagery,
entities involved have measurable extension (i.e., size, shape, or geometric characteristics),
it involves changes of distance, or clumping vs. separation along a gradient,
it concerns movement or motion (e.g., coming together, going/growing apart),
it concerns attraction and force,

and

it may be readily represented in terms of points, lines, areas, and trajectories.

The expert participants in this exercise noticed that certain highly spatial terms, such as 'region' and 'network', were missing. This prompted a similar search of the Geography for Life: National Geography Standards (Geography Education Standards Project 1994), in which region and network did appear, along with many other distinctive terms. All terms occurring in three or more standards were cross-referenced in a discipline interaction matrix (figure 12.2). Spatial terms (lexical concepts) unique to a single domain of science appear along the diagonal; terms found in multiple subject areas appear in the remaining upper cells, with counts in parentheses. The matrix should be instructive as we seek to find conceptual

	B - Physical	C - Life	D - Earth and space	Geography
B - Physical	object (10), atom (7), bond (7), wave (7), nucleus (6), emission (5), direction (4), mass (4), path (4), line (3), measurement (3), order (3), proportion (3), straight (3), wavelength (3)	motion (17, 3), interaction (8, 7), composition (7, 5), size (7, 5), scale (6, 4), movement (5, 4), molecule (4, 7), structure (3, 8) absorption (3, 3)	motion (17, 13), interaction (8, 3), composition (7, 6), force (11, 5), transfer (6, 3), movement (5, 12), position (5, 3), gravity (3, 3)	interaction (8, 7), distance (7, 5), size (7, 4), structure (3, 9)
C - Life		behavior (5), cell (5), external (4), storage (4), availability (3), coordination (3), hierarchy (3), level (3), organization (3), release (3), synthesis (3), unit (3)	containment (7, 3), interaction (7, 3), internal (7, 3), growth (6, 3), formation (3, 8), motion (3, 13)	environment (19, 15), structure (8, 9), interaction (7, 7), ecosystem (7, 5), containment (7, 4), transport (3, 8)
D - Earth and space			surface (8), cycle (6), plate (5), building (3), change (3), convection (3), earth (3), eruption (3), layer (3), matter (3), solid (3), system (3), volcano (3), weathering (3)	location (5, 14), containment (3, 4), erosion (3, 4), interaction (3, 7)
Geography				region (29), area (20), pattern (13), place (12), map (11), migration (10), distribution (9), settlement (9), spatial organization (8), center (7), access (6), connection (6), density (6), feature (6), exploration (5), neighborhood (5), network (5), route (5), site (5), boundary (4), expansion (4), global (4), landscape (4), local (4), proximity (4), shape (4), space (4), zone (4)

Figure 12.2

Spatial terms in science domains. Terms along the diagonal were tagged only in standards for that topic area. Terms in bold were tagged in standards for three of the four topic areas, with the exception of 'interaction' (the only term tagged in all four). Numbers in parentheses on axes are counts of standards having the tagged term. Only terms appearing in three or more standards are displayed.

threads between disciplines, but it also highlights the specialization of concepts distinct to specific subject areas.

Mapping concepts to teaching resources

A lexicon of spatial terms derived from the three studies referenced above aided the development of teaching resource collections for the National Science Digital Library, available within the NSDL master catalog at http://nsdl.org and published at the TeachSpatial website, http://teachspatial.org. For the annotations collection, a computer script ran 69 queries (sets of spatial terms from the 69 NSES grade 9–12 content standards) eight times each, once for each of the NSDL "pathway" subject domains (Chemistry, Geoscience, Life Science, Physics, Mathematics, Engineering, Social Sciences, and Space Science). The 3,000 distinct records returned were then culled to produce a new NSDL TeachSpatial collection of 2,476 teaching resources that align with one or more of the science content standards. We added 80 additional spatial learning resources from the Center for Spatial Studies at the University of California at Santa Barbara.

In the Resource Browser section of the TeachSpatial website, users can select any of the 129 terms in table 12.2 and get a list of links to free teaching resources relevant to that concept, in most cases from multiple science domains or disciplines. For example, a query for the term 'surface' returns four records with differing perspectives: those of earth science (ocean surface currents), mathematics (Archimedes' Law of Floating Bodies), biology (microbe behavior on surfaces), and physics (double curvature minimal surfaces in tensile structures). TeachSpatial provides a resource for instructors to add spatial content to existing courses in specific disciplines or, if so emboldened, to tap resources from several disciplines to highlight possible interdisciplinary transfer of spatial concepts in a more general course on spatial thinking.

Concept-Based Principles for a Course in Spatiality

All the work described thus far was originally motivated by the question "If there were a general course in spatial thinking at the undergraduate level, what would it cover?" To help answer this question, we identified the spatial concepts considered fundamental in a number of fields and found that most are meaningful in other, often disparate, fields. We then sought to learn which of the spatial concepts, principles, and skills appearing in K–12 curricula one could reasonably expect incoming college freshmen to be conversant with. However, while one can suggest that *scale* is a fundamental spatial concept for many fields, and should be well understood—*what is there about* scale that spatially literate people should know? Are there basic axioms or principles that concern scale? What scale-related tasks should they be able to perform? In addressing such questions, one can simultaneously invoke multiple concepts, joined through general spatial principles that span multiple fields. Thus, general concepts are building blocks for general principles and, in most cases, both principles and their component concepts have discipline-specific variation in meaning or perspective.

We find it most useful at this stage to organize fundamental spatial concepts and principles into several categories in a speculative course outline. We asked ourselves what conceptual content would lead to spatially literate students. This is a very different goal than achieving sufficient mastery in specialized spatial reasoning and computational methods to (for example) analyze landforms for their geological history, differentiate similar molecules from diagrams, or perform surgery. This high-level course would be foundational and motivational, diverse, even fun.

Such a course might best be co-taught—or at least co-designed—by a physicist, an astronomer, a biologist, a geologist, a geographer, a historian, a professor of literature, a cognitive psychologist, and an artist (or a similar combination). In lieu of such a committee, we will speculate on the contents of a course outline that such a group might produce. To do this, we will leap back and forth between spatial concepts such as those listed earlier and spatial principles—defined here as precepts, axioms, laws, or law-like statements underlying the practice of many diverse professions. As geographers, we admit to having only surface knowledge in most of these fields, along with a potential bias toward the geographic scales of phenomena. Nonetheless, we are intent on having the breadth of this imagined course span all fields for which "spatial is special" in some way.

A Course Outline: "Spatial Reasoning Across Disciplines"

Week 1: Space, time, and place

There are multiple ways to conceive, represent, and analyze space and spatiality.

Space and space-time

According to the online Oxford English Dictionary, the term 'space' implies "continuous, unbounded, or unlimited extent in every direction, without reference to any matter that may be present ... an attribute of the universe, describable mathematically." This corresponds to the naive conception of three-dimensional space as the void containing objects in the universe, or some portion thereof. The concept of *space-time*, an important theoretical construct in physics, is more difficult: time and space fused in a four-dimensional continuum within which all worldly phenomena exist, in a sense, as events.

Space and place

Space and place are sometimes used interchangeably, but more often differentiated, with space as an abstract construct described geometrically and place as "experienced space"—a subjective mental construction, possibly shared, and exemplified by "sense of place," a common phrase of uncertain origin. (See Tuan 1977.) The distinction becomes clear if you ask residents of a city to describe it verbally or to draw a map of it. Representations will differ, often radically. The area bounding the physical city and the position of things within it are spatial—that is, they have spatial extension and can be described geometrically. Alternatively, the distinctive memories of human experience in such spaces constitute places, such as Hemingway's Havana or the neighborhood of one's youth.

Location and position

Location is absolute, but descriptions of location are necessarily relative. We cannot say where something is (its position) without referring either to some other thing or to an arbitrary reference grid of some kind. Earth locations are normally described with coordinate points related to an estimated earth center. We also use qualitative terms of connectedness and distance to describe location in relation to other things. Topological terms such as 'adjacent', 'contains', 'overlaps', 'above', and 'north of' are amenable to formal definition; terms for qualitative metrics, such as 'near' and 'far', are highly contextual and less so.

Week 2: The nature of spatial thinking

Humans think in space, about space, and with space. Cognitive scientists have studied spatial thinking from at least three perspectives, each relevant for one or more of those contexts: spatial ability, acquired spatial reasoning skills, and use of spatial metaphor. We think in space as we maneuver through the world of everyday tasks and wayfinding, and about space as we reason about and analyze spatial configurations of natural phenomena. In both cases we draw upon spatial abilities such as mental imagery and spatial memory for making mental representations and for reasoning about alternative perspectives, cross-sections through objects, and transformations of material and objects over time—often aided by external representations, like maps, diagrams, and animations. There are individual and gender differences in such abilities (Hegarty and Waller 2006), but research is showing that performance at any level can be improved through instruction and practice (Uttal and Cohen 2012).

Spatial metaphor has been shown to be an essential reasoning strategy for non-spatial phenomena (Lakoff and Johnson 1980), i.e., thinking *with* space. Two commonplace examples of such spatialization are the "distance-similarity metaphor" (Montello, Fabrikant, Ruocco, and Middleton 2003) and "magnitude as size," as seen in concept maps, other network or graph representations, and statistical charts.

Cognitive maps and mental models

The term 'cognitive map' has been used in several senses. As introduced by Tolman (1948), it refers to the mental representations of the environment that humans and other animals will create and maintain, and which are consulted routinely in navigating around the house (or a maze), or through the town (or cage) they live in. The concept has been extended considerably in spatial and non-spatial ways—e.g., by environmental geographers studying the role of various cognitive processes in humans' mental models of space and place (Downs and Stea 1977) and as spatialized mental models of relations between diverse concepts.

Week 3: Spatial is special

There are several interwoven spatial principles that are fundamental and far-reaching across many scientific, engineering, and design fields. Their generality lies at the heart of why "spatial is special." A spatially literate person is familiar with the conceptual content of the principles and the fact of their generality.

Pattern and process; form and function

Kim Kastens, one of the experts who rated the spatiality of NSES content standards in the study by Grossner and Montello (2010), identified what she referred to as "spatial principle zero":

> A spatially literate person understands that the form, locations, and relative position of things in the universe contain meaning about the causes and consequences of their structure or arrangement, and should be able to provide examples from more than one field.

The spatial form of natural objects (their size, shape, structure, orientation, texture), at every scale, is strongly related to underlying processes of their creation and, particularly in the case of biological objects, to function. The form of earth features such as mountains, glaciers, and watersheds follow from processes we understand in large part by studying the spatial configuration and structure of their products. The composition and structure of organic and inorganic molecules are also functional, in that chemical processes both depend upon and produce them. The configuration of the solar system is the product of ongoing processes, but it seems a stretch to say they are functional. In a rather different sense, we say that cells, tree roots, thumbs, wings, and brains have any number of functions. Issues of purpose in these cases are often controversial, particularly outside scientific circles.

Human purpose plays an enormous role in the design of artifacts at all scales, from nano-scale robots to massive earthworks. With respect to chemical compounds, tools, vehicles, clothing, buildings, and cities, form largely follows function. Nevertheless, we like things that both work well and are pleasing to look at, so aesthetics of form can play an important role. Function is far less relevant to works of artistic expression, but aspects of spatiality are critical elements in the design of all artifacts, whether functional, purely artistic, or somewhere in between. Many associated concept terms hold meaning in other fields. For example, although *symmetry*, *perspective*, and *reference frames* are central to urban design, architecture, and most fine arts, symmetry and its close cousin *chirality* are also important for understanding molecular structure. *Perspective* and *reference frames* are central aspects of spatial cognition studied by cognitive psychologists.

Spatial context matters—at all scales, in all disciplines. Natural phenomena—things and happenings—are significantly affected by their surroundings (i.e., their environment or setting). This includes neighboring things and any networks or ecosystems they are part of.

What you can know depends upon where you or your sensors are and what you can perceive. Observations and analyses of phenomena occur within a reference frame. In very general terms this refers to situational and observational context: the spatial, temporal, and thematic bounds for what is being considered, along with associated measurement or classification systems. Reference frames can be global or local in absolute or relative terms, and resolution of representations can vary from fine to coarse (i.e., more or less generalized). As such, they are closely tied to concepts of *scale* and *granularity*. In physics, the motion of objects of interest and observers are essential determinants. In spatial analyses of social and natural phenomena at geographic scales, the bounds of a study area and areal divisions within it are critical factors influencing results and interpretations. Related concepts from the visual arts include *field of view* and *perspective*.

Near things tend to be more similar than distant things. Attributes of things that are near each other tend to be more similar than attributes of things that are far apart; such similarity leads to the identification of *clusters*, *regions*, and *neighborhoods*. This is a generalization of Tobler's First Law of Geography, which asserts this for scales associated with geographical space. Gravity models derived from Newton's Law have been applied in many fields (particularly in social science). Thus, the level of interaction between entities at two locations is a function of their mass (defined physically or otherwise) and declines in inverse proportion to some function of the distance between them.

The fallacy of independent observations

A spatially literate person will be aware that assumptions of independence for observational data in statistical studies are in many cases a fallacy. Whereas proximity is often an explanatory factor, many scientific models do not make location an explicit parameter. Hence, in cases where spatial association and dependence are factors but have not been modeled, statistical analyses may be flawed.

Spatial indexing aids knowledge discovery. To the extent that we georeference objects of interest in library and archive catalogs and in Web-accessible documents, adding spatial metadata, particularly for geographic locations, enables the discovery of spatial and spatial-temporal patterns that may be critical to understanding natural and social processes.

Week 4: Representation, part I—Size, scale, and error

Although every material thing has an absolute size in space, representations of its extent are relative to an ordered reference standard such as the metric scale of length. When something is seen as large or small, it is in relation to another thing or to a particular scale. A small elephant dwarfs the largest dog. On the scale of star size, our sun is small.

Graphic representations of things and designs are often made "to scale"—proportional to their actual size, faithfully rendering the relative sizes of their components. Representation scales are naturally related to the size of human beings. Representations can be at a smaller scale to visualize the entirety of something too large to see all at once, such as a house, a mountain, or a galaxy. Many realms of phenomena cannot be perceived directly without the use of tools and technology, such as microscopes, telescopes, and radiometers. In this case large-scale representations enable us to visualize things like the parts of a watch or a molecule with greater detail than is possible at their actual size.

Scientific and engineering disciplines are divided to some extent by scale. Although it is an oversimplification, we say the atomic and subatomic scales are the domain of physics; molecular scales the domain of chemistry, cosmic scales that of astronomy, and so on. The work of architects, planners, and environmental and social scientists involves scales associated with environmental and geographic space (Montello 1993).

Scale is an important consideration in art and in all design professions, and is linked to the concept of balance. Elements that are relatively large in one's field of view are said to have more weight, figuratively speaking, than smaller elements. Achieving a balance of graphical weight is often desirable, although deliberately unbalanced arrangements can be used to purposeful artistic effect too.

Many natural phenomena have a fractal nature (Mandelbrot 1983). That is, their structure is self-similar at any scale of observation. We see this when viewing higher and higher magnifications of crystals, for example. Clouds, river networks, and coastlines are said to have fractal qualities, though apparently this is only approximately true.

All representations are necessarily abstractions and tend to generalize away detail, making them the source not only of insight, but also error and uncertainty. This is true of internal representations (mental imagery, cognitive maps, and so forth) as well as graphical representations.

For graphical representations, greater resolution can mitigate that effect. The more pixels, points, or lines rendered per square centimeter of media (for screens, print, and film respectively), the higher the resolution and the greater the potential accuracy. For satellite imagery, a single point of data can represent an area of earth surface corresponding to anywhere between a few square centimeters and 1,000 square meters.

Week 5: Representation, part II—Objects and fields

Objects can be viewed as discretizations of material phenomena (e.g., storms, ancient figurines). Depending on the scales of observation, representation, and analysis, natural phenomena can be viewed variously as continuous fields, as discrete objects, or both. Fields represent values of some attribute for every point in a region of space-time, and are most useful for studying essentially continuous phenomena. For example, the atmosphere has (potentially) a different temperature at every point in space (or space-time). Representation choices are pragmatic, in part a function of desired resolution or granularity. For example, thunderstorms can be represented as continuous fields or as discrete objects having trajectories. But, at some scale, the boundary between storm and non-storm is difficult to discern. Viewed at larger scales, many continuous phenomena are composed of discrete objects (the water droplets and oxygen molecules of a storm), and we often discretize regions of continuous phenomena and material substances having similar attribute values as objects of study (thunderstorms). Some archeological finds are clumps of material whose identity as intentionally fabricated objects may be contestable.

Week 6: Spatial structure, part I—Clusters and regions

One goal of scientific analysis is the discovery of spatial structure—instances of identifiable patterns that can be classified as objects in their own right and compared. One such structure is the *cluster*, the identification of which can depend upon many factors: the original hypothesis, the scale of analysis and reference frame, theory-driven categorical attributes and threshold values for them, and the type and quality of measurement instruments, to name a few. We discover and study clusters of things of every conceivable scale, including nanoparticles, cell, diseases, people, and stars.

Another highly general spatial structure is the *region*. Like clusters, regions exist in nature, but their identification likewise depends upon subjective definitional criteria in many cases. Regions can be purely spatial (anterior, northern, central) or be defined as areas having similar values for one or more attributes (common activity, geology, belief, demographics, etc.). That is, they are human-created objects of analysis. The concept of region is primarily associated with geography and astrophysics, but a recent scan of the Corpus of Contemporary American English for terms completing the phrase "region of the _____" yielded 'gene', 'cell', 'sky', 'ship', 'neck', 'bat', 'brain', 'rotor', and 'amygdala' in addition to the expected 'country' and 'world'. This suggest that the term 'region' is often applied to approximate locations on or within something, with no precise boundary implied.

Week 7: Spatial structure, part II—Networks, connection, and interaction

Networks exist throughout nature (e.g., watersheds, circulatory systems, proteins, lightning, neurons), they are the essential structure of many human artifacts (e.g., transport, utilities infrastructure), and they are an invaluable method of representing connectivity and interaction of all

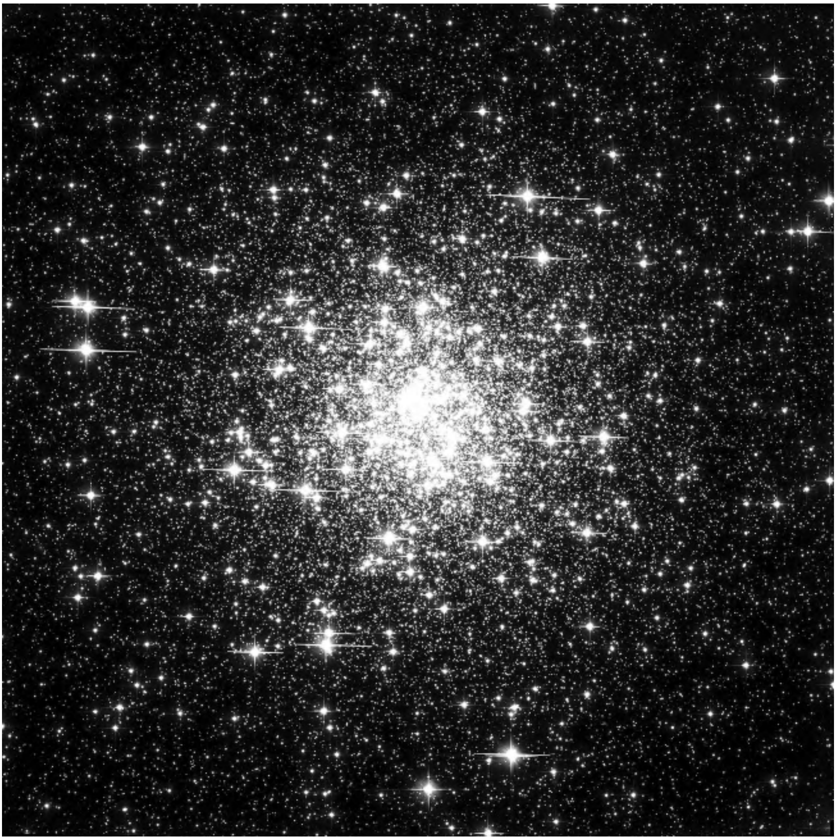

Figure 12.3
The globular star cluster Messier 69. Credit: NASA/STScI/WikiSky.

kinds. Network science is an increasingly important interdisciplinary field, with a formal mathematical foundation in graph theory. A spatially literate person will be familiar with the basic principles of networks and graphs, and will recognize network structures in science, engineering, and social behavior, and in the global spatial interactions of the highly connected twenty-first-century world. Networks are composed of nodes and the links between them. Nodes can be any material or non-material thing—a city, a person, a concept. They can be hierarchically ordered in multiple ways, according to a magnitude derived either from intrinsic properties or from network measures like connectedness (degree) or centrality. Links can be any material or non-material connection or association between nodes. They can be directed, undirected, or mixed, and have a magnitude (weight) derived from potential or actual flows or interaction on them. Graphs are the mathematical expressions of network structure, and many descriptive terms and measures are used interchangeably for both graphs and networks. Graphs can be represented as matrices of numbers and as node-link diagrams.

Week 8: Spatial dynamics

The processes that produce spatial patterns are dynamic; they occur over time whether or not analyses focus on or reflect that fact. A significant proportion of the phenomena we observe, measure, and analyze in seeking explanation concerns spatial change: change of position, form, orientation, and spatial identity (e.g., composition in parts, splitting, and merging). The same holds true for many forms of humanistic inquiry and expression, in history and the fine arts for example.

Concepts in spatial dynamics are relevant in many fields and at most scales. Most have precise meanings in physics and chemistry, and alternate but similar or metaphorical meanings in other fields. For example, in physics 'diffusion' refers to a random walk of particles in a heat exchange process where a high concentration of a finite number of particles spread throughout a solution. In other fields, diffusion can refer to the spread of a concept or practice from one or more locations to many more. Meanings of 'migration' are largely consistent between disciplines. In the sciences, 'flow' refers to the continuous movement of matter (normally fluids) in a stream-like fashion; it is also used metaphorically—and effectively—to refer to non-material things (such as ideas), and to non-fluids (such as currency in trade activity).

Week 9: Spatialization

Spatialization is the use of spatial concepts and their linguistic and graphical representations to reason and communicate about non-spatial concepts. Lakoff and Johnson (1980, p. 17) have demonstrated the pervasiveness of spatial metaphors in the English language, and assert that "most of our fundamental concepts are organized in terms of one or more spatialization metaphors." A few important examples include similarity as distance; time as distance; associations of any kind in topological terms (adjacent, overlapping, containment, connection); and magnitude of any type or by any measure, as size. A spatially literate person will recognize the practice of spatialization in information visualizations, including Venn diagrams, flow charts, concept maps, scatter plots, line and bar graphs, and network diagrams.

Week 10: Critical spatial thinking and analysis with representations
A spatially literate person is proficient at critically interpreting the most common forms of graphical representation of spatial data at all scales: maps, plans, and diagrams. They are also able to read and critically evaluate graphical spatializations of non-spatial information, from the scatter plots, line graphs, and bar charts used for visualizing statistical data, to the network diagrams describing the relationships between people or concepts, or the flow charts depicting dynamic procedures and processes. Critical interpretation is informed in both cases by many of the principles and concepts discussed earlier—particularly in Week 4—concerning scale, generalization, and accuracy. Interpretation must also be informed by an awareness of the subjective nature of data selection, the limitations of spatial tools, and the underlying assumptions of descriptive and predictive models.

A spatially literate person will also be able to understand and use spatial language for conveying relationships of proximity, connectivity, and containment.

Discussion and Conclusions

We have described a multi-year, multi-phase research effort motivated by a belief in the value of making both the importance and breadth of spatial concepts, reasoning, and skills more explicit at the lower-division college level. We identified spatial concepts and principles found in teaching standards, course content, and research investigations across a variety of fields within the physical and social sciences, design disciplines, and, to a lesser extent, the arts and humanities. Among the results of that work are the TeachSpatial Web portal for spatial teaching and learning resources (http://teachspatial.org) and the establishment of a minor in Spatial Studies at the University of California at Santa Barbara.

In this chapter, we identified sets of spatial concepts and principles that are both fundamental and trans-disciplinary. Recognizing that most spatial concepts and principles have discipline-specific applications and perspectives, we organized them within an outline for a prospective "course for spatial literacy." The course is aimed at college freshmen, although we anticipate that this work may also be useful for developers of K–12 curricula. By beginning the enumeration of a set of spatial concepts, principles, and skills that we should expect college freshmen to have some proficiency in, we hope to encourage incremental steps toward making a "spatial thread" within existing K–12 content standards more explicit, thereby reducing the need for spatial remediation at the college level. Spatial literacy offers a pathway to informed problem solving in a broad range of human endeavors; it is within reach of nearly everyone, and it should be a goal of basic education.

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