Daniel Ness, Stephen J. Farenga, and Salvatore Garofalo

SPATIAL INTELLIGENCE

WHY IT MATTERS FROM BIRTH THROUGH THE LIFESPAN

ROUTLEDGE

SPATIAL INTELLIGENCE

Spatial Intelligence examines public and professional conceptions of the relationships between thinking about spatial attributes and active engagement in spatially related constructions and designs. Even though children's and adolescents' spatial propensities in constructive activities parallel the skills needed by professionals in both established and emerging fields, spatial education is often missing from K-12 curricula and is easily impeded by teachers, parents, or other individuals who do not provide contexts in formalized settings, such as schools, to nurture its potential. This book bridges the gap by linking the natural spatial inclinations, interests, and proclivities of individuals from a variety of cultures with professional training and expertise in engineering, architecture, science, and mathematics. Educators will be better able to achieve the skills and awareness necessary to provide children and young adults with the vital opportunities inherent in spatial education.

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Why It Matters from Birth through the Lifespan

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We dedicate this book to Professors Herbert P. Ginsburg and James H. Borland at Teachers College, Columbia University. Their constant encouragement, mentorship, and support in our research endeavors provided us with the inspiration that contributed to this book's development.

CONTENTS

PROLOGUE

Spatial thinking is ubiquitous; it occurs in both our subconscious and conscious lives. At times, we operate spatially when we use our subconscious to navigate from one place to another. It is not uncommon, for instance, to hear people report arriving at a destination without being aware of how they got there. Every day, people leave work, get in their cars, and drive home without a remembrance of a single landmark. A good deal of time, we are involved in completing activities without even being aware that they rely heavily on spatial thinking skills. Examples include the spatial orientation of notes on a musical score, mathematical symbolism (e.g., fraction notation), and the process of interior decorating a home.

At other times, however, we are consciously aware that we are required to use cognitive skills that rely heavily on spatial ability. Examples in this case include graphic design, interpreting an architect's blueprint, and working with geometric figures. Seven shapes that are commonly known as tangrams are shown in Figure 0.1. While looking at these shapes, notice that there is no specific order in their arrangement. The shapes are placed on the page, each with its own individual properties and attributes. We ask readers to examine these shapes and then mentally arrange them on the page to create one unified shape in the form of a square. When completing this task, see Figure 0.2 for one possible solution.

This challenge provides an example of the difficulty in tapping critical, multi-layered spatial thinking skills, and how diverse humans are in their abilities to use spatial thinking skills when solving problems. In attempting to complete this puzzle, which represents a visuo-spatial task, some people may be able to rotate and manipulate the shapes mentally, while others would find it more conducive to re-represent the situation at hand through drawing or cutting the pieces out and having a physical model for manipulation. Still, others might find it easier to

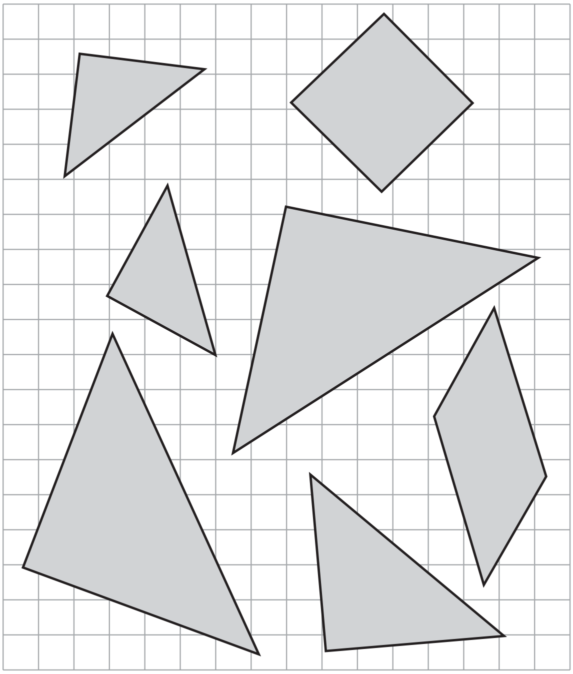

FIGURE 0.1 Random Placement of Tangrams

solve a problem like this one through verbal discourse and logic. Each of these methods provides some insight into the various modes of cognitive functioning that humans display.

In this book, we take a global view of spatial intelligence through its intrinsic connections to practical, theoretical, and empirical domains of inquiry. That said, care must be taken when one attempts to classify complex behaviors because there is often overlap and integration of content represented by the subskills that comprise these behaviors. Such is the case when considering how to discuss and examine a psychological construct like spatial intelligence. Psychological perspectives on spatial thinking and cognition research have focused primarily on empirical and theoretical approaches to inquiry. Less emphasis has been placed in the spatial literature on the practical aspects of how spatial thinking can be used in our everyday lives. However, in recent years, researchers have devoted more attention to the study of the use of spatial skills in terms of its applicability in careers, education, and everyday activities. Accordingly, each of the chapters in this book challenges the idea that spatial thinking is detached from our daily lives; instead, we consider the manner in which spatiality plays an intrinsic part of our everyday existence. In fact, spatial cognition is not only an area of inquiry in and of itself, but also a skill set that provides a foundation

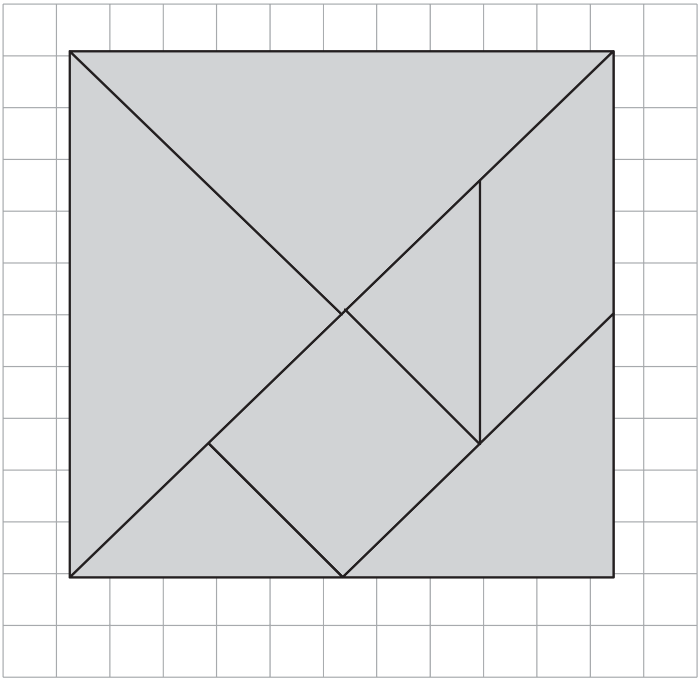

FIGURE 0.2 Solution to the Tangram Problem at the Beginning of this Prologue

that is necessary to both understand and conduct many life activities. This can be seen from children's block building, as discussed in Chapter 8, to an engineer's working of an architect's blueprint of a planned structure discussed in Chapter 7. Each of these activities demonstrates the human ability to start with contemplative, abstract concepts that eventually lead to real-life structures that may engender functional characteristics.

From a theoretical standpoint, spatial intelligence can inform the reader how to generalize about spatial constructs within the human experience. In Chapter 6, we connect the theoretical perspective of affordance with the use of visuo-spatial constructive play objects (VCPOs)—examples of which include blocks, bricks (such as Lego), and planks. Our definition of affordance with regard to spatial intelligence differs from the typical psychological view, which contends that affordance enables the individual to advance through prompts and sensations that are attributed to the object or place. In contrast, we argue that the greater the affordance of an object, the less it will allow the individual the opportunity to think creatively and to fully understand the essence of the object's properties in relationship to form and function. In Chapters 2 and 3, we highlight the development of spatial thinking models through an examination of five theoretical positions: Piaget and Inhelder's theory of the child's concept of space; the Vygotskyan socio-cultural perspective on spatial cognition; the nativist perspective on spatial thinking; the interactionist approach; and a-posteriori universalism.

From an empirical perspective, spatial intelligence research can be quite informative in explaining differences in spatial ability, development of spatial cognition, and the effect of spatial thinking on inquiry-related behaviors. In Chapter 4, we devote our attention to the influence of biological factors such as genes and hormones and their influence, combined with environmental conditions, on the development of spatial intelligence. Our notion of *g* to infinity reflects our position that the conception of intelligence has expanded from a unitary construct into a vast set of factors that include spatial ability as one of the prime components of intelligence. Therefore, we consider spatial intelligence to be the "hidden intelligence" that supports the successful completion of many everyday activities that we engage in. Spatial intelligence encompasses a skill set that some recognize as practical intelligence, where outcomes from an activity are tangible. As a hidden intelligence often overlooked in formal educational settings, spatial intelligence is firmly engrained in the work of mechanics, kitchen designers, cartographers, and many other professions. To account for the importance of thinking about space in practical terms, we explore the relationships among navigation, mapping, and spatial awareness in Chapter 5. Through the examination of Seymour Papert's theoretical framework for learning called constructionism, which grew out of the basic principles of Piagetian constructivism in which cognitive development precedes and influences what can be learned, we have sought out connections between technological advances and the development of spatial thinking. Accordingly, explorations in the use of technology and its intrinsic connections with spatial intelligence are discussed in Chapter 9. In Chapter 10, we broaden the scope of spatial intelligence by viewing it through the ecological lens, and examine how the natural landscape influences spatial development. In this chapter, we discuss spatial dominance, which refers to the human desire to manipulate and organize space. Spatial dominance is an attempt to control the environment in which we come into contact, and arrange it in a manner that is suitable to our needs.

In Chapter 1, we begin our discussion of spatial intelligence by considering the importance of spatial thinking as a means of understanding and interacting with the physical world. We then consider the views of a diverse group of specialists in space and spatial thinking. This group comprises physicists, mathematicians, psychologists, architects, engineers, geographers, philosophers, and educators.

From the combined content of all ten chapters in this volume, we posit that spatial intelligence is truly a basic intelligence, or as we are concerned, a primal intelligence that serves as a keystone to all considerations of spatial ability upon which many other activities depend. In this volume, we explore how spatial intelligence is developed, displayed, and acted upon throughout our lives. Now we return to the initial challenge at the beginning of this prologue. Were you able to find a correct pattern and complete the tangram puzzle successfully to meet the challenge? Whether successful or not is unimportant. What is important is that one begins to realize the ubiquitous nature of spatial thinking and its close relationship to everyday activity in a theoretical, empirical, and practical manner.

Because the risk of leaving out a key individual when considering the development of an "Acknowledgments" section is considerably high, we, the authors, are culpable for any oversight that may be apparent between this book's covers. Indeed, any work such as this one is only possible by the sifting, winnowing, and labor of others who have come before us to share their insight and findings through publications and presentations to advance knowledge and scientific thinking. Thus, we atone for any omission that we have made in our acknowledgments.

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New York, New York

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THE SPATIAL DEFINITION

A Time-honored Enigma

> *There's the added element of adrenaline if you're performing. You're aware of spatial relationships and the music.*
>
> Kim Gordon

We begin our journey on spatial intelligence by introducing four figures that are shown in pairs. While examining these pairs, special attention should be placed on how they compare and contrast with each other. Moreover, consider the following questions: first, what is the significance between each pair of figures? And second, what relationship exists, if any, among all diagrams in each of the four pairs? Before answering these two questions, consider each photograph or diagram in each of the four figures (Figures 1.1, 1.2, 1.3, and 1.4).

As for the first question, what is the significance of Figure 1.1? We begin by emphasizing the need to represent objects, in this case, water molecules, as spatial representations. In Figure 1.1 a sixth grader, who did not yet learn specifically about water molecules in the science curriculum, was asked to represent her version of the behavior of water molecules in a one-liter flask containing approximately a half liter of liquid water just reaching the boiling point (100°C or 212°F). Her depiction of this account is astonishingly accurate—namely, her visual representation of the liquid water molecules show greater density and packedness in terms of proximity of location than that of the water vapor above the liquid water line. The water vapor shows more separation between molecules. It is also worthy of note to analyze our interpretation of the sixth grader's spatial representation. In our own interpretation, we use terms like "proximity," "above," and "separation" to explain her visual representation. At the same time, from a cognitive perspective, if asked to represent a situation or phenomenon using a diagram, the sixth

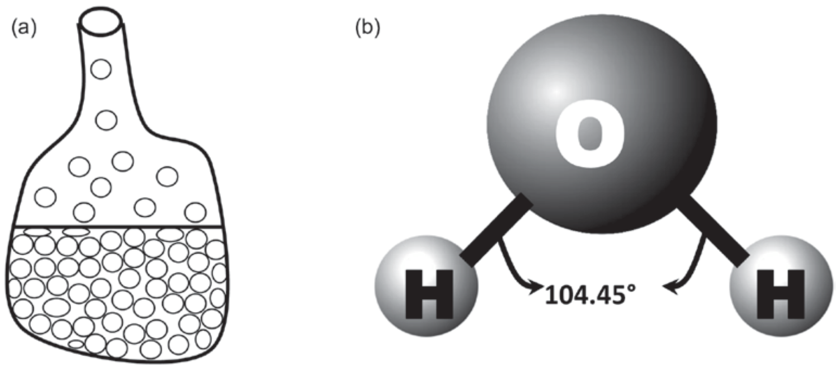

FIGURE 1.1 A sixth-grade student draws a pictorial representation (a) of the density of water molecules in a one-liter flask containing approximately a half liter of liquid water at boiling point (100°C or 212°F). A tenth-grade student (b) learns how to represent the elemental composition of a water molecule in a chemistry class

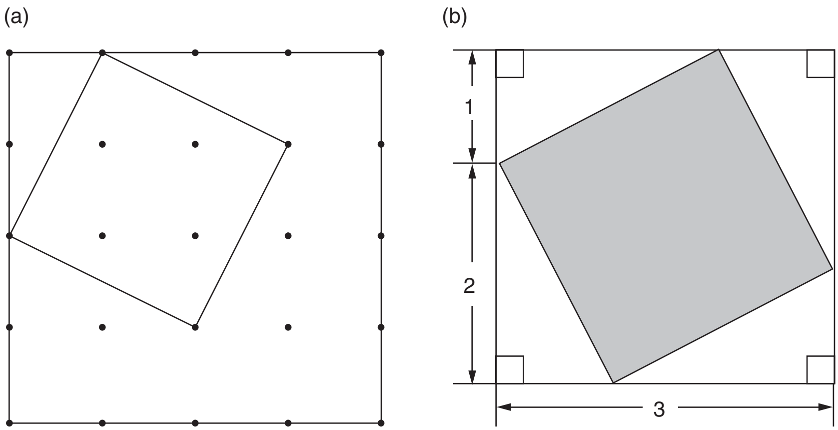

FIGURE 1.2 A fourth-grade student (a) constructed two squares—one 16 square units and the other 5 square units—using a Geoboard with elastic rubber bands. An eleventh-grade student (b) is preparing for a college entrance examination with a question that asks for an area of a given square with included side lengths

grader clearly cannot escape representing the task without employing constructs of spatial relations. The same case can be made with regard to Figure 1.1 on the right, namely, the tenth grader who is learning about the atomic composition through a visual account of the water molecule. What is fascinating here is that even at the atomic or microscopic level of physical reality, it is still possible to represent something spatially. Further, spatial considerations are given to the angular positioning of the two hydrogen atoms in relation to their bonds to the single oxygen atom—a measure that approximates 104.45 degrees. In most chemistry

FIGURE 1.3 Dr. John Snow, a nineteenth-century physician from London, tracks the number of cases of cholera by constructing a map (shown) and traces the illness to a water pump in the London community of Soho in 1854 (a). Using Geographic Information Systems (GIS), epidemiologists on the border of the West African countries of Sierra Leone and Guinea identify settlements surrounded by dense tropical forests that are likely to increase human interaction with fruit bats, one of the main vectors of the Ebola virus (b)

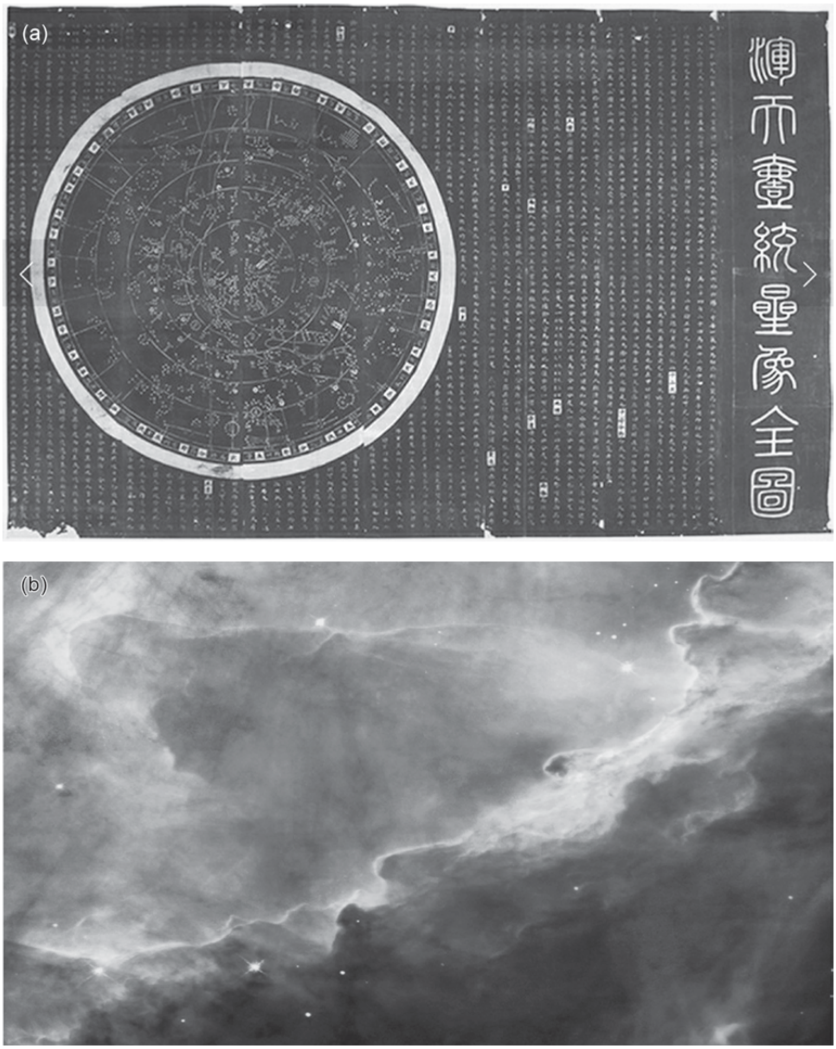

FIGURE 1.4 The Suzhou Star Map rubbing (a) is a stellar constellation map that influenced calendar reform in late twelfth-century China. The Swan (Omega) Nebula is a Hubble Image that captured a vast ocean of gleaming hydrogen gas with smaller quantities of oxygen, sulfur, and other elements as well. This Hubble photograph (b) shows a small section within the Omega Nebula, also known as Messier 17 in the constellation Sagittarius—a breeding ground for star formation

Photo courtesy of NASA.

curricula, it is imperative for chemistry teachers to cover the angular positioning of atomic bonds within any given molecule. Through the lens of the water molecule, angular positioning of hydrogen atoms is important to learn because these figurations indicate how a single water molecule interacts with other water molecules. The topic of angular positioning of atoms in intra-molecular bonding clearly exemplifies the need for students to think spatially, both in terms of their understanding and in terms of eventual expertise in chemistry-related fields. Not only are these depictions spatial—i.e., spatial representations—but their referents, in other words, the water molecules themselves, are spatial, too.

What about the significance of parts (a) and (b) of Figure 1.2? Figure 1.2a is a photographic representation of a Geoboard—a mathematical manipulative that is used to help students improve their conceptual formations of mathematical concepts, particularly those in geometry. In this specific Geoboard spatial representation, we can say that the rubber band that depicts the larger square consists of 16 small squares. Notice how the pegs, depicted by the dots are represented in terms of organization; they are neatly organized in rows and columns, and the distance between each peg can be considered equal to one unit. That is, a 1 unit × 1 unit square is equal to one square unit. The outer rubber band thus creates an inner square whose area is 16 square units. Moreover, if we stipulate that sides representing diagonals divide a rectangle into two congruent right triangles, it is then possible to determine the area of the interior square—five square units (we leave the explanation for the area of this square to the reader). The main idea here is that we are thinking and considering all the parameters involved in this example from a spatial perspective. Now, in terms of Figure 1.2a, b determining the area of a given square as a question on a college entrance examination, notice the similarity between this depiction of a square and the inner square represented in Figure 1.2a; without question, they are strikingly similar. In fact, the answer to the question in Figure 1.2b is the same answer that we find when determining the area of the inner square in Figure 1.2a. Again, these two visuals demonstrate spatial considerations; there is essentially no way around it. Students and other individuals who are introduced to the Geoboard or the question posed in Figure 1.2b are in essence required to think spatially. Again, notice our language when analyzing Figure 1.2a: "formation," "geometry," "square," "organization," "rows," "columns," "distance," "square unit," "inner," "area," "sides," "diagonals," "rectangle," "congruent," "outer," "right triangles," "constructed," "Geoboard"—these are all spatial terminology. Regardless, from a cognitive perspective, anyone who comes into contact with a Geoboard or a question such as the one asked in Figure 1.2b will be required to exhibit and use spatial thinking skills.

Next, what is the significance of parts (a) and (b) of Figure 1.3? To begin with, both diagrams demonstrate how spatial thinking plays a dynamic role in the field of epidemiology. Dr. John Snow, who developed methods that many would argue catapulted the field of epidemiology—the study of diseases and the spread of diseases by various contagions—into the limelight of medical and academic research, generated a map of Soho that listed all, or most, of the cholera cases in the Soho vicinity by indicating individual cases of cholera using hash marks. Snow produced this map in 1854—a time when contemporary technology included the nascent stages of the daguerreotype, steam engine, and processing mills. In other words, GIS, as we know it in the twenty-first century, did not exist, and all cases had to be documented by hand or etched onto paper. Early epidemiology was a dangerous way to earn a living in 1854 because the extent to which one could come into contact with tainted drinking water (in the case of cholera) or infectious disease (such as tuberculosis) was exponentially higher than it is today; the Industrial Revolution in Great Britain was more than 60 years in the making, and this resulted in part, with large numbers of families moving into urban areas, thus making the opportunity for spreading contagious disease all the more possible. Further, Snow's proto-epidemiological search and investigation during the late summer of 1854 occurred nearly a century before antibiotics were developed and used to treat infection and deadly maladies. To be sure, Snow demonstrated something very important with respect to his map of Soho: spatial thinking skills can enable us to grapple with adverse, and oftentimes life-threatening situations of utmost criticality. By identifying cases with hash marks on a map of Soho, Snow was able to identify the cause of the upsurge of cholera cases in the Soho vicinity—a well with a water pump serving the community tainted water with potentially deadly cholera bacteria.

In comparison to Snow's diagram, Figure 1.3b is a GIS image of the border between Sierra Leone and Guinea near the west coast of Africa. This image is a magnificent example of a twenty-first-century version of Snow's epidemiological map of 1854. Given that fruit bats were determined to be one of the main lines of transmission of the Ebola virus, and that this species of bat depends primarily on dense tropical forest and wetlands environments for survival, it was critical for physicians and Red Cross personnel to hone in on specific locations where fruit bats congregate. While dense rain forests are key for fruit bat survival, fruit bats carrying the Ebola virus were found primarily where they can get sources of nourishment—namely, oil palm trees. The GIS snapshot in Figure 1.3b shows buildings and other human dwellings outlined on the right and oil palm cultivations outlined on the left. The need for spatial thinking with respect to this image is unequivocal—the groves where the fruit bats congregate are within yards from communities with homes and other buildings where people do business and other forms of transactions in everyday life. Clearly, distance and proximity—both spatially charged concepts—impact the extent to which Ebola infection may occur.

What about the answer to the first question with respect to Figures 1.4a? As we indicated previously (p. 4), the Suzhou Star Map rubbing is a representation of constellations that led to changes in the Chinese calendar system during the late twelfth century. Astronomers during the twelfth century completed the star map that connects concepts of space with time. Through the innovations of this star map, the Chinese calendrical system influenced later astronomical representations, such as that of the Tenmon Bunya no Zu that was conceived and worked out by Harumi Shibukawa on the orders of the Japanese shogunate with the intention of revising the lunisolar calendar in the late seventeenth century. Figure 1.4a differs from all previous examples in that the Suzhou Star Map rubbing is a representation of space on a macro level—as it represents galaxies and related features of the universe. So, too, does the picture in Figure 1.4b. Consisting of hydrogen gas and other elements, Swan (Omega) Nebula, a Hubble image, shows a swath of space that is approximately 5000 to 6000 light years from earth and some 15 light years in diameter. As we have indicated earlier, Messier 17 is only a section of the entire Swan Nebula—a star formation hotbed (no pun intended). Both Figures 1.4a and 1.4b demonstrate space on a massive scale. Space on the macro level—"outer space"—is often the way in which many individuals refer to space. At the very least, it is the way in which most people use the term in the everyday context.

We move on to the second question posed: what relationship exists, if any, among all diagrams in each of the four pairs? In answering this question, we refer to the work of Urie Bronfenbrenner and his contributions to ecology as it relates to human development as we consider the notion of ecological space (2009). Just as understanding the earth from an ecological perspective—such as the categories of species, population, community, ecosystem, and biosphere—can shed light on the nature of environmental change, so, too, is it possible to reflect on human development and cognition in general and space or spatial thinking in specific through the lens of an ecological framework. Thus, the relationship of each of the eight depictions in Figures 1.1 through 1.4 is evident when considering spatial cognition from an ecological perspective. From an ecological standpoint, then, Figures 1.1a and 1.1b clearly exemplify what specialists in spatial cognition would refer to in ecological contexts as a micro system in spatial thought. Next come Figures 1.2a and 1.2b—what we believe falls into the category of the meso-system of spatiality. This is because our encounters with Geoboards and (spatial) test questions are physically experienced in our everyday lives; they are things we can describe clearly in that they are in proportion within our visual field, and, therefore, can be utilized and discussed through sight and touch. Figures 1.3a and 1.3b, we argue, fall into the category of the exo-system of spatial thought. This has to do with the fact that these depictions—the physical map of Soho in London and the bird's-eye view of an Ebola-affected region—cannot be touched or viewed in the same manner as a book or a Geoboard because their referents are relatively larger spaces than items in our local environments that can be compared to our personal contexts; at the same time, they are not large to the extent that we are unable to fathom where something is located within a map or in a GIS. In contrast, Figures 1.4a and 1.4b are difficult to conceptualize within our local contexts. Again, this has to do with our contexts in comparison with those of stellar environments—those that are almost entirely bereft of personal perspective.

To explain this phenomenon, we refer to books, periodicals, or the Internet as examples. Go to nearly any news website on the Internet. You will undoubtedly encounter a story about a newly found exoplanet, a Goldilocks exoplanet (one that may be suitable for life), up-to-date research on the oldest galaxy to date, a sighting of a black hole. The list goes on. To be sure, newly discovered events, not only in our solar system, but just about anywhere in the universe, are posted as news stories at a near-exponential rate. The point is that we're so far away from these events that it is next to impossible to identify an actual and real representation of objects in space at this level, what, in ecological terms, would be referred to as the macro system, or astronomical space. The depictions of newly discovered phenomena that are parsecs from Earth are virtually always depicted in a way that is described by astrophysicists. We often see new exoplanets, for example, with captions that read: "An artist's depiction of Planet X" and the like. So, in reconceptualizing the meaning of spatial thinking, it is important to consider the ecological model as a starting point in research and analysis of space and spatial thinking. All systems within the ecological framework are important in a variety of ways that affect our lives—from the spatial relations at the atomic level to those of the Goldilocks exoplanet that may be many parsecs from Earth.

So, based on the answers to the two initial questions that begin this chapter, we can safely argue that spatial thinking is universal—literally. However, our analysis of these diagrams and photographs leads us to a time-honored enigma: what is spatial thinking? Restated, what is space?

The Importance of Spatial Thinking

In the second edition of *Geography for Life: National Geography Standards*, the National Council for Geographic Education (NCGE) revised its standards to emphasize the need to include spatial thinking as an essential topic in the geography curriculum (NCGE, 2012). In fact, Sinton, Bednarz, Gersmehl, Kolvoord, and Uttal (2013) addressed the need for spatial thinking in geography by organizing this area of inquiry around four domains: life spaces, physical spaces, social spaces, and intellectual space. Examples of life spaces include those having to do with the fundamental concepts of location, scale, and movement and the idea that we live and make plans in space. The notion of physical spaces involves the idea that humans modify their physical environments while that of social spaces involves the idea that space can be construed in terms of culturally relevant norms, such as playgrounds, school zones, and neighborhoods. The idea of intellectual space has to do with how humans construe space in terms of how everyday things or ideas can be designed, planned, or organized. As a school subject, geography was a staple of the school curriculum during most of the twentieth century. However, with the onset of content standards during the 1980s, geography seemed to have been downplayed in school curricula, and since that time, geography content was integrated in the subjects of social studies and physical science. This has resulted in a meager treatment of spatial thinking in the K-12 curriculum, and in cases where the subject of social studies lacks discussion of geography, spatial thinking has been absent altogether (Holcomb & Tiefenbacher, 1989; Unwin, 2013; Winter, 2009).

While NCGE has made important inroads in addressing the importance of spatial thinking skills in geography, organizations representative of mathematics and science have either done so tangentially or have not clearly articulated the topic. Given its emphasis on English language arts/literacy and mathematics, the Common Core State Standards Initiative (CCSSI) has attempted to present a comprehensive overview of these important subjects. Yet within the mathematics component of the CCSSI, it is difficult to pin down any indication of spatial thinking as a significant component of mathematical knowledge (CCSSI, 2010). The closest implication of spatial thinking in the CCSSI Mathematics Standards can be found in Standard 4.G.A.3, which emphasizes symmetry, or Standards 8.G.A.1, 8.G.A.2, 8.G.A.3, and 8.G.A.4, which address geometric transformations, namely, reflections, rotations, translations, and dilations. Likewise, the Next Generation Science Standards (NGSS) is sorely wanting with regard to spatial thinking skills (NGSS, 2013). Although NGSS has alluded to spatial constructs in two standards (MS-ESS2-2 and HS-ESS2-1, middle-school and high-school earth science, respectively), nowhere prior to these seemingly demanding experiences do students have familiarity with specific content skills involving spatial thinking. Thus, based on the literature in the fields of cognition and education, it is unrealistic to expect students to think spatially in a deliberate and routine manner when engaging in these complex activities because doing so makes the learning experience difficult and frustrating (Bransford, Brown, & Cocking, 2000).

It is important to articulate the relationship between the K-12 school curricula with spatial skills because the ability to think spatially has become an indispensable part of numerous professions and practical applications (Kell & Lubinski, 2013). It would seem quite necessary, then, to render the teaching of spatial ability a recognized and required educational objective. To do so would be natural because the conceptual narrative emphasized in the NCGE, Common Core, and NGSS standards (Reys, 2014) parallels the conceptual constructs inherent in spatial thinking.

From a developmental perspective, the study of young children's spatial thinking can enhance our understanding of spontaneous geometric propensities that are closely related to the study of science, technology, engineering, and medicine (STEM). Spatial thinking ability is a cross-cutting skill that overlaps several content areas (STEM, language, social sciences, and arts and humanities, to name a few). Even after accounting for verbal and mathematical ability, it has been shown that higher spatial ability predicts interest and success in STEM disciplines (Newcombe, 2010; Wai, Lubinski, & Benbow, 2009; Verdine et al., 2014). Key findings from NASA's systems engineering studies support our assertion that students must be exposed to physical construction materials prior to moving to the digital representations. Several reasons account for the cognitive transition from physical models to more abstract understandings of space. Despite excellent marks in college and superior research backgrounds, younger engineers had more difficulty when working in ambiguous situations than did older engineers (Brown, 2009). Further, younger engineers were found to engage in less creative reasoning when compared to older engineers (Casey, Jarvis, & Amatucci, 2008; Williams, & Derro, 2008). Archer and Lloyd (1982) state "in older children that there is a clear relationship between high spatial performance and experience with three-dimensional forms—for example wood working, model making, or toys such as Lego and Meccano" (p. 236). Siann (1977) suggests that certain activities that are linked to spatial ability are also considered traditionally masculine or feminine and may only be encountered if appropriate to one's gender. As noted by Johnson (1984), if the science curriculum is built around interest, attitudes, and experiences that are present for one sex and not the other, identical treatment of the sexes will only accentuate the inequity. The same holds true for the mathematics curriculum as well.

While the ability to think spatially is an essential skill for school as well as success in the professional world, it may often seem hard to define. There has been general agreement in the literature, particularly in the areas of cognitive psychology and geography, about what spatial thinking is. Among the community of geography scholars, spatial thinking has been defined as "an ability to visualize and interpret location, position, distance, direction, relationships, movement, and change over space" (Sinton et al., 2013, p. 44). Clearly, this ability taps requisite skills necessary to become an architect, engineer, physician, scientist, and even artist. The NRC's Committee on Support for Thinking Spatially claimed that "the key to spatial thinking as a constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning" (NRC, 2006, p. 12). In light of these definitions, we have defined spatial thinking as one's ability to perceive, recognize, or conceptualize physical or intellectual constructs in terms of their position or location in both static and dynamic systems. What these three definitions have in common is the idea that spatial thinking involves one's interpretation and representation about space and constructs within it. Examples of spatial thinking skill sets include, but are not limited to, conceptualizing space, using tools of representation, reasoning and proving, problem finding, problem solving, visualizing relationships, analyzing static and dynamic systems of objects, observing how objects behave in their environment, recognizing the relationship between two- and three-dimensional constructs, and differentiating between Euclidean space and other geometric models. It should be pointed out that the spatial skill sets mentioned are vital in learning about relationships between tension and compression, columns and beams, trusses, and arches—concepts inherent in engineering principles. Equally important to note is that the act of spatial thinking can be, on the one hand, a deliberate activity involving intent and purpose and, on the other, one that is spontaneous and unplanned. As

Sinton et al. (2013) point out, "Spatial thinking is a constant and pervasive act in which we all participate, at times automatically and intuitively and at other times very methodically and deliberately" (p. 15).

So, we know from experts in the fields of spatial cognition and neuroscience that spatial thinking skill is an important factor not only in success and accomplishment in several professions and occupations, both within and outside STEM disciplines, but also as a way to go about numerous activities of everyday life. But even with the growing corpus of research literature on spatial thinking that has shown the benefits of spatial thinking skill, for example, that experience with mental rotation and spatial change detection tasks in infancy and early childhood predicts high levels of mathematics performance of four-year-old children (Bonny & Lourenco, 2015), or the high correlation between spatial skills and STEM disciplines (Uttal et al., 2013), it is nevertheless next to impossible to pin down precise meanings of "space" or "spatial."

The Elusiveness of Spatial Thinking

Our discussion and interpretation of the discourse regarding the elusive nature of the terms "space" and "spatial" that we present on p. 8 are not new. In her extensive examination of multiple interpretations of space and spatial representation, Lynn Liben (1981) describes our seemingly intuitive and spontaneous ability to describe space and spatial representation on the one hand, and our ambiguity to define these terms on the other. Liben begins with an account of the definition of space, and outlines in a fitting manner the parallelism between the evolutionary progression from absolute to relative space and from the Euclidean paradigm to non-Euclidean representations of space:

> Just as there has been a shift from absolute to relative spatial concepts in physics, there has also been a shift from an exclusively Euclidean, three dimensional model of space, to non-Euclidean models of space with the possibility of more than three dimensions. (p. 4)

Liben continues:

> The distinctions between place and space . . . foreshadow a distinction drawn . . . between "environment" and "spatial abstraction," that is, a distinction between location or places in particular, and spatial concepts or abstraction in general. (p. 5)

This distinction between place and space is intrinsically connected with ideas regarding psychological space and physical space. Liben points out that, contrary to the views of many cognitive psychologists who argue in favor of compartmentalization of these spaces—namely, psychologists study psychological space and physicists study physical space—the two spaces are intertwined and not mutually exclusive. An understanding of psychological space presupposes the study of spatial behavior and spatial representation. Liben (1999) has us also reconsider what it means to understand spatial representations in general and external spatial representations in particular. By introducing the seemingly simplistic view of the so-called transparency model, that is, the notion of representing an external referent in a generally direct and somewhat spontaneous process, Liben suggests a more complex model, referred to as the embedded view, one that takes into account a constructivist perspective in which the child interacts with her environment. To this end, spatial representation is not solely based on sensation, as in a manner derived by stimulus-response, but one centered on the cognitive developmental view that integrates one's place in space.

Liben (2006) revisited the problems of terminology with respect to "space" and "spatial" by broadening the audience on the topic of spatial thinking. Similar to our rationale for writing this text, Liben set out to address three main audiences: scholars in cognition and spatial thinking; budding scholars who are beginning to recognize and appreciate the interplay between research and practice; and practitioners and caregivers. One type of symbolic artifact that has the potential to increase awareness through connections of space and spatial thinking to our everyday lives is the map. Indeed, maps have multiple purposes and functions. Perhaps the most commonly perceived purpose is the identification of direction between or among two or more locations through the process of locomotion (i.e., getting from one place to another by walking, riding, driving, boating). As Liben emphasizes, maps also help us record and store information and make sense of data either through exploration or summarization—as in the case of an informational map that includes figures regarding varying quantities of resources or social preference (e.g., political candidate inclination). In sum, the map is categorized as a specific type of spatial representation, namely, a spatial product, that can serve as a useful starting point in education and spatial thinking skills. It is with the map that education for spatial thinking needs to be made explicit (Vygotsky, 2012). Unfortunately, with marked, adverse changes in school curricula over the past three to four decades, geography has become a steadily lifeless subject, one that has been deconstructed; its components have been made diffuse in a way that smatterings of its subject matter have been reduced to bits of content in other subjects, such as history, earth science, and political science. The slow evolution of the marginalization of geography has left the skill set connecting spatial skills with everyday experience in an indeterminate state.

Liben notes the evolving nature of individuals with that of physical entities and humans' changing spatial representations of these entities. As an example, one need only look at a photograph of a community street scene, say, 75 or 100 years ago, and a Google Map image of the same scene today in order to appreciate her point regarding evolving environments and the potential role they play in developing spatial education curricula to be embedded in current school subjects.

In sum, what is fascinating about Liben's earlier and later accounts of the problem with definition is how numerous dichotomies are brought to debate, especially those that have, from a historical perspective, caused great confusion in the quest for understanding space and spatial thinking. Liben's earlier studies, then, form the backdrop of a highly arguable issue—and that is the problem of definition of "space" and "spatial" [thinking].

The Polysemy of Spatial [Thinking]

The word "polysemy," meaning literally many ("poly") signs ("semy"), is a term not often used in everyday discourse. But it makes a great deal of sense when it applies to the terms "space" and "spatial." The *Oxford English Dictionary* defines polysemy as "The coexistence of many possible meanings for a word or phrase." This definition is particularly applicable when referring to a word's semantic structure. Thus, from a polysemic perspective, the task of exacting a singular definition of "space," or of "spatial," is so difficult to accomplish that even experts in numerous fields in the social and natural sciences have found it exceedingly difficult to do so as well.

When a noun is modified by the adjective "spatial"—such as "spatial thinking," "spatial cognition," "spatial sense," "spatial ability," "spatial orientation," and the like—we are almost always at a loss when attempting to arrive at a definitive meaning. To frustrate matters further, this lack of definition is no novelty; it has been an enigma for millennia and remains so to the present day. As a word, "space," as well as "spatial," is a polysemy—a term with multiple meanings and definitions. History has shown that the terms "space" and its derivatives—"spatial thinking" with respect to the topic of this book—are elusive. In this chapter, and in the book, while we may convince most readers in setting the record straight, as it were, to find the meaning behind anything spatial or spatially related, the meaning of the term clearly has been a conundrum for practitioners and scholars throughout history.

Views of a diverse group of specialists in space and spatial thinking (including physicists, mathematicians, psychologists, architects, engineers, geographers, philosophers, and educators) and analyses of these perspectives follow.

Albert Einstein

In illustrating the difficulty in defining "space" or "spatial," we proceed in this section by providing a historical backdrop of anecdotes by scholars, philosophers, and laypersons, many of whom have had to grapple with using the terms "space" and "spatial" in their work and in their specific science. We start with a classic quote by one of the twentieth century's—and some would argue history's—most influential people: Albert Einstein. The following quote by Einstein essentially sums up the difficulty in defining something spatial. Einstein wrote the following passage in his Foreword to Max Jammer's book *Concepts of Space: The History of Theories of Space in Physics* (1954).

> If two different authors use the words "red," hard," or "disappointed," no one doubts that they mean approximately the same thing, because these words are connected with elementary experiences in a manner which is difficult to misinterpret. But in the case of words such as "place" or "space," whose relation with psychological experiences is less direct, there exists a far-reaching uncertainty of interpretation. (p. xiv)

Like Einstein, Jammer was a world-renowned physicist. So, the term "space" that Einstein discusses in the quote broadly refers to how it might be used within the context of a construct in physics. Regardless, his point is loud and clear: the meaning of "space" is nebulous; the term conjures up different meanings to different people when uttered, even more when context is lacking or unavailable. Einstein points out that certain words are difficult to misconstrue because their usage prevents any room for misapprehension. He uses the words "red," "hard," and "disappointed" as examples. When one refers to a red car, red hair, or "all red in the face," we know that the speaker is referring to color. Even if one were to use the phrase "in the red," which is not based on the color red, the meaning is crystal clear—namely, a cliché to describe someone or some entity that owes money. In short, the use of "red" in a sentence indicates clarity of meaning. So, too, the use of "hard." While the word "hard" has multiple meanings, its context makes the term definitive. "Hard" can mean "difficult" or "physically inflexible."

Not so for the words "space" or "place," words that are so elusive that their very use can lead to even more complexity. The word "space" is all the more elusive in meaning when considering the role of word choice based on contextual associations. What better word can psychometricians and test preparers use on standardized test questions when testing language concepts or meaning within reading passages? "The word 'space' in the passage most nearly means . . . ." This all depends on the context of the passage. So, if finding the definition of "space" is so difficult to pin down, doing so for the term "spatial thinking" is certainly no easy task either.

Elizabeth Fennema

Next, we turn to an anecdote from an eminent mathematics education researcher, Elizabeth Fennema, Professor Emeritus from the University of Wisconsin, Madison. The following excerpt comes from Fennema's article entitled "Mathematics, Spatial Ability and the Sexes," a paper she had presented in 1974 at the annual meeting of the American Educational Research Association in Chicago.