Geological Society of America
Special Paper 413
2006

# Spatial thinking in the geosciences and cognitive sciences: A cross-disciplinary look at the intersection of the two fields

**Kim A. Kastens**[†]
*Lamont-Doherty Earth Observatory and Department of Earth & Environmental Sciences, Columbia University, Palisades, New York 10964, USA*

**Toru Ishikawa**[‡]
*Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964, USA*

## ABSTRACT

**Learning geoscience and becoming a professional geoscientist require high-level spatial thinking. Thus, geoscience offers an intriguing context for studying people's mental representations and processes as they pertain to large-scale, three-dimensional spatial cognition and learning, from both cognitive science and geoscience perspectives. This paper discusses major tasks that professional geoscientists and geoscience learners deal wit h, focusing on the spatial nature of the tasks and underlying cognitive processes. The specific tasks include recognizing, describing, and classifying the shape of an object; describing the position and orientation of objects; making and using maps; envisioning processes in three dimensions; and using spatial-thinking strategies to think about nonspatial phenomena. Findings and implications from cognitive science literature that could be incorporated into geoscience teaching and some questions for future research that arise from examination of the intersection of the two branches of science are also discussed.**

**Keywords:** spatial cognition, geoscience education.

## INTRODUCTION

In this paper, we look for common ground within the domain of spatial thinking between the fields of geosciences and cognitive sciences. Learning geoscience and becoming a professional geoscientist require extensive high-level spatial thinking. Thus, from a cognitive science perspective, geoscience offers an intriguing context for studying people's mental representations and processes as they pertain to three-dimensional spatial cognition and learning. From a geoscience perspective, cognitive science may be able to shed light on why many geoscience learners have difficulty with certain spatially intensive tasks, how expert geoscientists' thought processes differ from novices', and how students' progress toward expert thought processes can be fostered.

We begin by identifying and describing some of the geoscientist's tasks that require thinking about objects or processes or phenomena in space, the kind of thought processes that we broadly call spatial thinking. Then we look for insights and lines of inquiry in the cognitive science literature that could shed light on how expert geoscientists and geoscience learners accomplish those tasks. This paper's mapping of the

---

[†] E-mail: kastens@ldeo.columbia.edu.

[‡] E-mail: ishikawa@ldeo.columbia.edu. Ishikawa now at the Center for Spatial Information Science, University of Tokyo, Japan.

Kastens, K.A., and Ishikawa, T., 2006, Spatial thinking in the geosciences and cognitive sciences: A cross-disciplinary look at the intersection of the two fields, *in* Manduca, C.A., and Mogk, D., eds., Earth and Mind: How Geologists Think and Learn about the Earth: Geological Society of America Special Paper 413, p. 51–74, doi: 10.1130/2006.2413(05). For permission to copy, contact editing@geosociety.org.

connections between geoscientists' mental processes and cognitive scientists' research findings is not exhaustive; it is merely an early step in what we hope will be an ongoing dialog between these two fields. Our intended audience is both geoscientists and cognitive scientists. We hope that geoscientists and geoscience educators find insights that will sharpen their own thought processes or enable them to better understand their students' difficulties. We also hope that cognitive scientists find questions that trigger new lines of inquiry.

We consider three groups of geoscience tasks: (1) describing and interpreting objects, (2) comprehending spatial properties and processes, and (3) metaphorical usage of spatial thinking. The first group of tasks includes:

- describing the shape of an object, rigorously and unambiguously;
- identifying or classifying an object by its shape;
- ascribing meaning to the shape of a natural object; and
- recognizing a shape or pattern amid a noisy background.

The second group of tasks includes:

- recalling the location and appearance of previously seen objects;
- describing the position and orientation of objects;
- making and using maps;
- synthesizing one- or two-dimensional observations into a three-dimensional mental image; and
- envisioning the processes by which materials or objects change position or shape.

And the third group of tasks includes:

- using spatial-thinking strategies and techniques to think about nonspatial phenomena.

Collectively, such thought processes are at the heart of virtually all fields of geosciences. Furthermore, researchers have shown that spatial ability and thinking play important roles in many fields of science and engineering, including physics, chemistry, mathematics, engineering, geoscience, and medicine (Carter et al., 1987; Downs and Liben, 1991; Mathewson, 1999; Pallrand and Seeber, 1984; Piburn, 1980; Rochford, 1985; Russell-Gebbett, 1984; Tuckey and Selvaratnam, 1993). Therefore, space is a unifying theme across many disciplines. Spatial thinking in geosciences spans a huge range of scales, from the atomic (e.g., the crystalline structure of minerals) to the global (e.g., atmospheric circulation patterns).

In articulating those geoscience tasks, we focus on two end-member categories of thinkers: (1) pioneering geoscientists, at the frontiers of science, undertaking a spatial challenge for the very first time that it has ever been done; and (2) beginning students, undertaking a spatial challenge for the first time it has been done by them.

For additional insights into spatial thinking by geoscience learners in an educational context, we refer the reader to Kastens and Ishikawa (2004) and Ishikawa and Kastens (2005). For additional insights into spatial thinking across a range of disciplines, we recommend National Research Council (2006).

## DESCRIBING AND INTERPRETING OBJECTS

### Describing the Shape of an Object, Rigorously and Unambiguously

#### *The Geoscientist's Task—Describing the Richness of Nature*

Faced with the huge range of objects found in nature, early mineralogists, petrologists, geomorphologists, structural geologists, sedimentologists, zoologists, and botanists had to begin by agreeing upon words and measurements with which to describe these natural objects. Given a collection of objects that intuitively seem related in some way, what should one observe, and what should one measure, in order to capture the shape of each object in a way that is rigorous, unambiguous, and includes all of the important observable parameters?

After much spatial thinking, crystallographers decided that they should observe how many planes of symmetry the crystal has and the angles between those planes of symmetry. Size and color of the crystal are not so important. After much spatial thinking, structural geologists decided that they should describe a fold in a sedimentary layer by imaging a plane of symmetry of the fold, and then measuring the orientation of this axial plane, and how much the fold axis departs from the horizontal.

The mental processes of pioneering observers of nature as they develop a new description methodology include (1) careful observation of the shape of a large number of objects; (2) integrating these observations into a mental model of what constitutes the shared characteristics among this group of objects; (3) identifying ways in which individual objects can differ while still remaining within the group; and (4) developing a methodical, reproducible set of observation parameters that describes the range of natural variability within the group. Step 4 may include developing a lexicon or taxonomy of terms, developing new measurement instruments, developing new units of measurement, or developing two-dimensional graphical representations of some aspect of the three-dimensional objects (Fig. 1).

Geoscience novices learning to describe objects of nature professionally must first become facile with the terms and techniques used by specialists who have previously studied this class of objects. In some cases, these descriptive techniques may call upon spatial skills that many learners find extremely difficult. Examples include the technique by which structural geologists capture the shape of a folded sedimentary layer by projecting vectors perpendicular to the fold onto a lower-hemisphere equal-area projection diagram (Fig. 1A), and the system of Miller indices by which mineralogists describe the angular relationships between the faces of a crystal (Fig. 1B).

#### *Insights from the Cognitive Science Literature—Topological, Projective, and Euclidean Spatial Concepts*

In the cognitive science literature, Piaget's developmental theory has been very influential. Piaget and Inhelder (1948

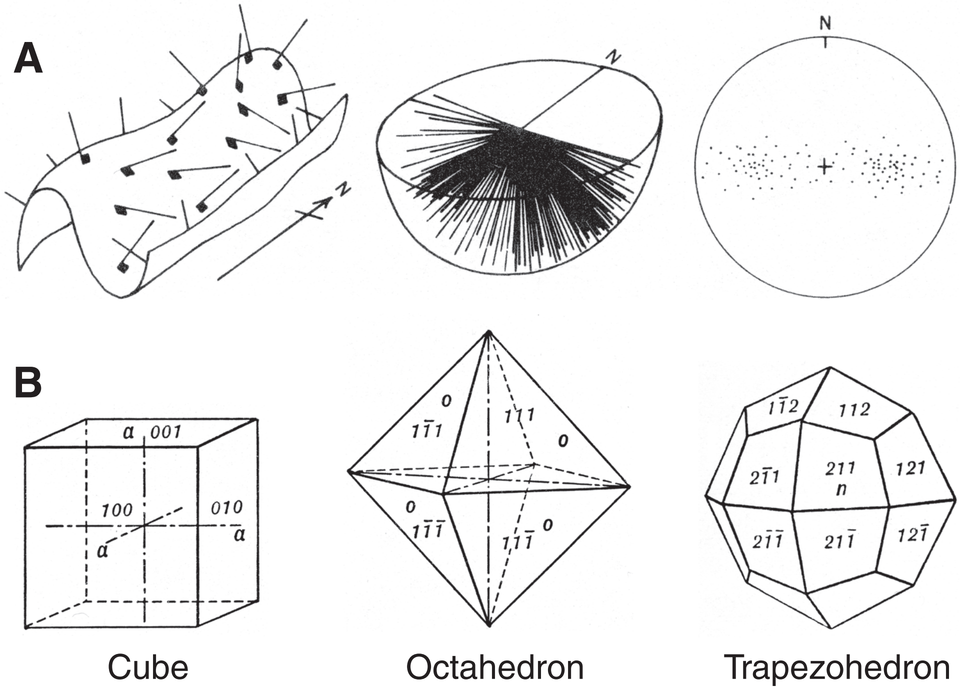


Figure 1. Examples of the specialized representational techniques that geoscientists have developed to describe the shape of natural objects. (A) The lower-hemisphere equal-area projection that structural geologists use to describe the shape of a folded sedimentary stratum. Left: The lines represent vectors that are locally perpendicular to a rock surface, in this case a folded rock surface. Middle: These vectors are projected downward from a common origin until they intersect an imaginary hemisphere. Right: This hemisphere is then projected onto a plane by an equal-area projection. The general trend of points in this representation records and conveys the overall shape and orientation of the rock surface, while the scatter of the points conveys the irregularity of the surface (reproduced with permission from Hobbs et al. [1976, Fig. A11]). (B) The system of Miller indices with which mineralogists describe the angular relationships between the faces of a crystal. A set of three coordinate axes is defined, with its origin in the center of the crystal, and a vector is drawn from the origin perpendicular to each crystal face. The Miller index of a crystal face is the *a-b-c* coordinates of the point where the vector intersects the crystal face, normalized to a unit length. For example, in the cube, the vector from the origin intersects the front face of the crystal at point (1, 0, 0), so the Miller index of this face is 1 0 0. A number with a bar on top is negative (reproduced with permission from Hurlbut [1971, Figures 66, 67, and 75]). In Piaget and Inhelder's (1948 [1967]) classification scheme of three spatial concepts (topological, projective, and Euclidean), the fold-description task requires the projective spatial concept, while the crystal-faces task draws heavily on the Euclidean spatial concept.

[1967]) classified spatial concepts into three categories: topological, projective, and Euclidean. Topological spatial concepts involve only qualitative relationships such as separation, order, and continuity (e.g., "next to," "between," "inside/outside"). Projective spatial concepts encompass understanding of spatial relations tied to a specific viewpoint and differentiation of various viewpoints; for example, the ability to imagine (1) the shape of a shadow that would be cast onto a screen by a geometric shape held at various angles to a light source or (2) what a scene would look like if viewed from several different vantage points. Euclidean spatial concepts contain metric information, such as distance, direction, and angle, coordinated in a fixed frame of reference. Piaget and Inhelder argued that children understand topological space before projective and Euclidean spaces. Understanding of projective and Euclidean spaces emerges in parallel at approximately the same developmental stage, but the Euclidean spatial concept takes longer to be fully comprehended.

When we look back at the geoscientist's tasks from this perspective, we find that many of the descriptive tasks that geoscience learners find most difficult have a strong projective or Euclidean component. For example, the structural geologist's lower-hemisphere equal-area representation of the shape of a fold (Fig. 1A) requires use of the projective spatial concept to envision the outcome of projecting multiple vectors onto a surface simultaneously. The mineralogist's Miller indices (Fig. 1B) require use of the Euclidean spatial concept to compare the crystal faces against a hypothetical three-dimensional coordinate system. This suggests that expert geoscientists have more sophisticated projective and Euclidean spatial concepts, gained through repeated practice, than (even adult) geoscience novices do. In fact, Downs and Liben (1991) found that a significant portion of college students performed poorly on tasks that required accurate understanding of projective and Euclidean spatial concepts.

## IDENTIFYING OR CLASSIFYING AN OBJECT BY ITS SHAPE

### The Geoscientist's Task—Classifying a Newly Described Object

Having described a natural object using the professionally arrived-at vocabulary and techniques discussed in the previous section, the geoscientist then classifies the object into a group or category. Paleontologists or micropaleontologists classify fossils or microfossils according to their morphology; geomorphologists do the same with landforms. Traditionally, mineralogists or petrologists (scientists who study rocks) identify minerals in a hand sample or photomicrograph by shape, color (including color changes under different lighting conditions), and texture (e.g., Does it have stripes? Does it have a shiny surface?) (Fig. 2A).

Geoscience novices learn this skill by comparing unknown fossils, minerals, or geomorphological features against a catalog, using the descriptive terms and measurements mentioned above. To become experts, students must construct their own mental catalog of the properties of dozens to hundreds of fossils or minerals, and then develop facility at comparing each unknown new mineral or fossil against this mental catalog.

### *Insights from the Cognitive Science Literature—Categorization*

Such a task has been studied in cognitive psychology under the heading *categorization*. Categorization is one of the most basic characteristics of human thinking; in fact, it has been of interest since the era of Aristotle. Linguist George Lakoff said, "There is nothing more basic than categorization to our thought, perception, action, and speech. . . . Without the ability to categorize, we could not function at all, either in the physical world or in our social and intellectual lives. An understanding of how we categorize is central to any understanding of how we think and how we function, and therefore central to an understanding of what makes us human" (Lakoff, 1987, p. 5–6).

How do people categorize? The traditional view maintains that a list of attributes, individually necessary and jointly sufficient, defines what is or is not a member of a category (defining-attribute theory). One of the earliest and most famous examples of this theory is Collins and Quillian's (1969) semantic network model, in which concepts are represented as hierarchies of interconnected nodes (Fig. 2B). Each node, or concept, has associated defining attributes (e.g., a bird has wings, can fly, has feathers). Subordinate concepts share the defining attributes of their superordinate concepts (e.g., a bird breathes, eats, has skin). Collins and Quillian predicted that, if knowledge is mentally represented as such a network, it should take more time to verify a sentence that relates two concepts farther apart in the network than to verify a sentence with concepts near each other. For example, people should take more time to verify the sentence "a canary is an animal" (the two concepts are two links apart in the hierarchy) than the sentence "a canary is a bird" (one link apart). They found that people's verification times were consistent with this prediction.

Later, it was pointed out that categories are often not clearly defined by a finite set of defining attributes; rather, categories have fuzzy boundaries. In the face of such criticism, some researchers proposed prototype theory (e.g., Rosch, 1978). This theory maintains that members of a concept vary in their typicality (e.g., a robin is a more typical member of the concept *bird* than an ostrich), and that category membership is determined by the degree of similarity (or family resemblance) to the category's prototype (i.e., the best example).

Geoscientists use classification schemes that resemble the cognitive scientist's defining-attribute theory, semantic network model, and prototype theory. A geoscience example of the defining-attribute strategy for classifying objects is the venerable Udden-Wentworth scale (Blatt et al., 1972) for classifying sedimentary grain sizes, in which all grains between 2 mm and 62 µm in diameter are classified as sand, grains between 62 µm and 4 µm are classified as silt, and so on. The hierarchies of Collins and Quillian's semantic network model resemble Carolus Linnaeus taxonomic hierarchies (Farber, 2000). A geoscience example of the prototype strategy for classifying objects is the manner in which a species of fossil (or living organism) is defined by reference to a specific individual of that species preserved in a museum; other individuals are classified as members or nonmembers of that species based on their resemblance to the so-called type specimen (International Commission on Zoological Nomenclature, 1985; Simpson, 1940). Each of these classification schemes was developed in the earliest days of natural history, and remains in use today.

Most geoscientists would probably argue that the early natural scientists developed different kinds of classification schemes for different types of natural objects because the relationships among those objects do, in fact, vary in nature. Sedimentary grain sizes vary along a continuum from extremely fine to extremely coarse, so the "obviously sensible" way to categorize clastic sediments is to define attributes that mark the boundary between one category and the next. Fossils usually do not fall along a continuum of physical characteristics; instead they tend to display clusters of characteristics, so the "obviously sensible" way to categorize them is by resemblance or nonresemblance to an ideal or prototype. But faced with the cognitive science finding that the human brain may inherently favor certain ways of forming categories, geoscientists have to ask whether our classification schemes truly reflect what is out there in nature. Do we use "sand/silt/clay" because these terms represent natural categories of sediment that differ in their depositional and erosional processes? To what extent are our classification schemes a product of our brains' facility for categorizing? Do we use "sand/silt/clay" because these categorical labels are easier for our brains to think about than the fairly arbitrary numerical values that have been chosen to subdivide the natural continuum? A resolution of this question may lie in evolutionary psychology (see e.g., Tooby and Cosmides, 1992). The lives of ancestral humans were domi-

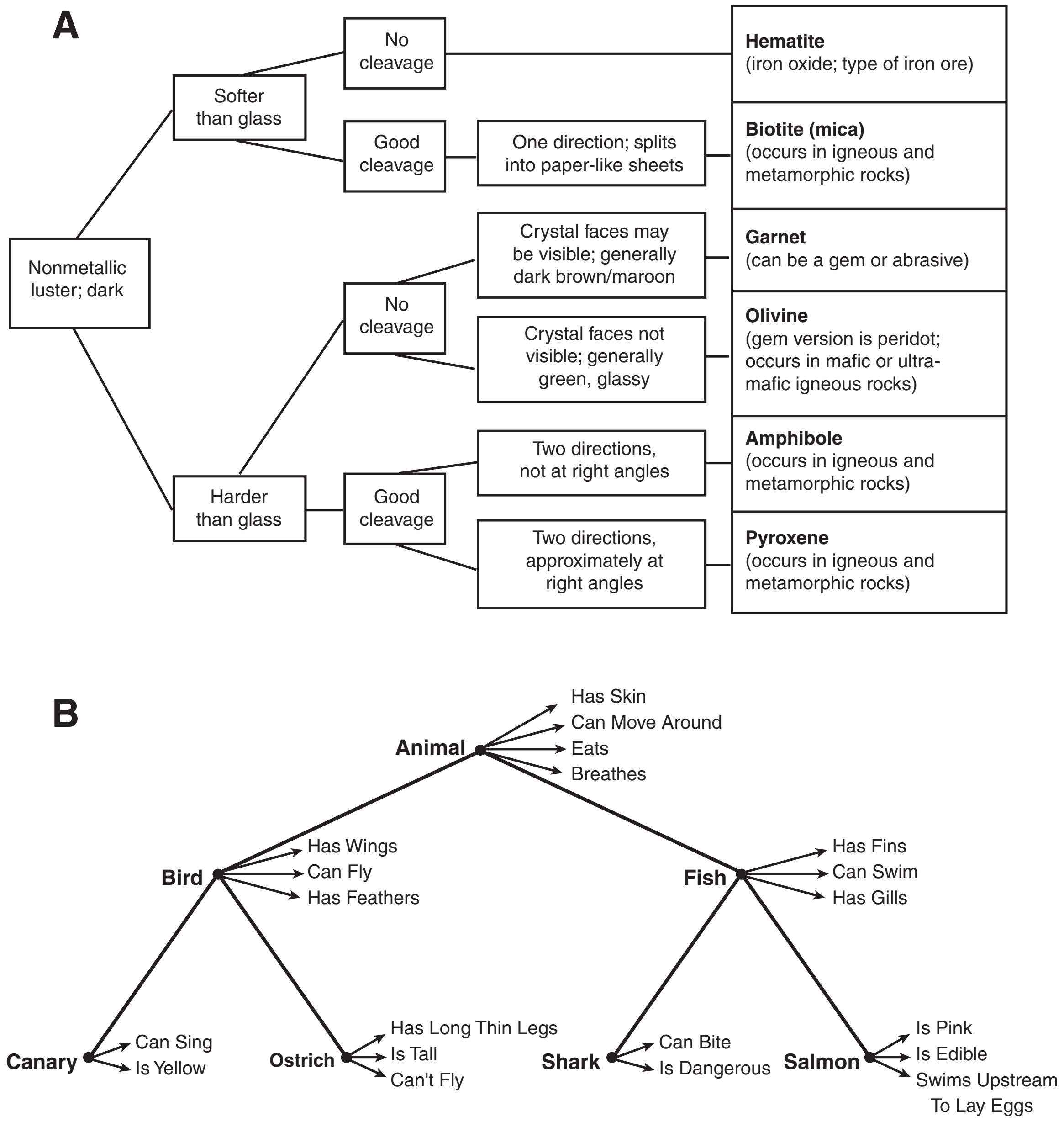


Figure 2. Classification of objects according to their shapes. (A) Example of a hierarchical system for classifying Earth objects, in this case minerals, according to shape and other visible characteristics (adapted with permission from Marshak [2001, app. B-2]). (B) Collins and Quillian (1969) hypothesized that concepts are represented mentally as hierarchies of interconnected nodes (adapted with permission from Collins and Quillian [1969, Fig. 1]).

nated by the same natural objects that concern today's geologists and ecologists: plants, animals, rocks, and landforms. Thus the human brain may have evolved the ability to organize concepts into categories according to patterns common in nature. Then natural scientists exploited that mental capacity to develop formal and intricate classification schemes (see also the discussion about object location memory in a following section).

## Ascribing Meaning to the Shape of a Natural Object

### *The Geoscientist's Task—Inferring History and Formative Processes*

The shape of a natural object (including its size and orientation) carries clues about its history and formative processes. To begin with the most famous examples of ascribing meaning to the shape of natural objects in the history of geosciences, Alfred Wegener (Wegener, 1929) noted the jigsaw fit of the coastlines of Africa and South America, and inferred that the continents had previously been connected (Fig. 3A). James Hutton (Hutton, 1788) noted the contrast in tilt and texture of underlying and overlying rocks at Siccar Point in Scotland, and inferred the existence of unconformities and the immensity of geologic time (Fig. 3B).

Among modern geoscientists, micropaleontologists use morphologic clues to infer both the geologic age and the paleoenvironment within which planktonic microfossils lived and died (Fig. 3C). If one sample of diatom (a form of phytoplankton) fossils has thick silicate shells, whereas another group has delicate, thin shells, this could be attributed to the latter group growing in a water mass impoverished in dissolved silica. If the carbonate-shelled microfossils (foraminifera) in a sediment sample are pitted and lacking delicate protuberances, this could be attributed to the sediment sample being deposited near the calcite compensation depth, the depth in the ocean below which carbonate dissolves. The observation that a group of microfossils is much smaller than typical for their species could be attributed to their living in a stressed environment, for example a marine species living in brackish water (Kennett, 1982).

Structural geologists look at distortions in the shapes of crystals and fossils to infer the strain (and thereby the stress) that a body of rock has undergone (Ramsay and Huber, 1983). Sedi-

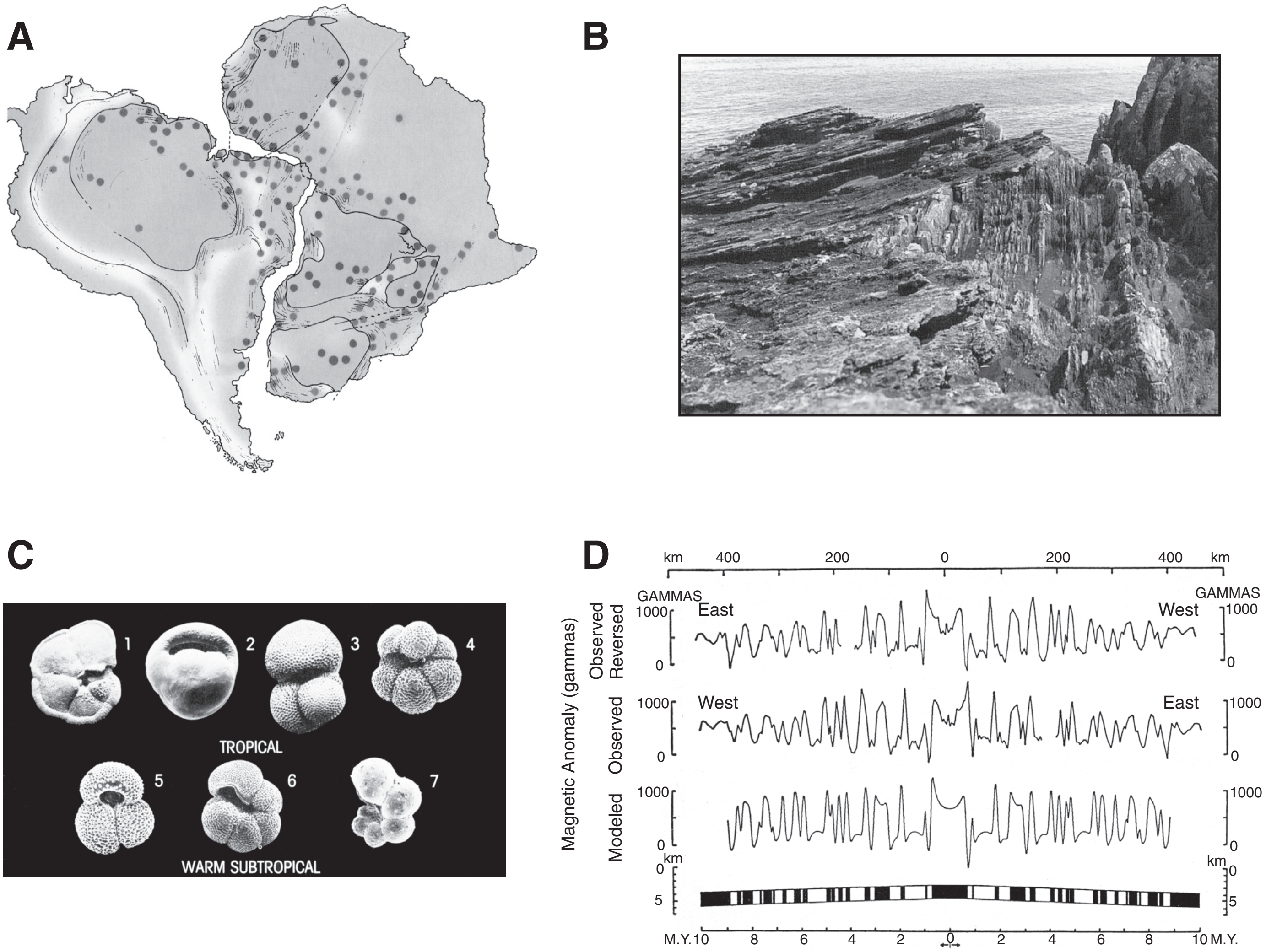


Figure 3. Examples of how geoscientists ascribe meaning to shapes. (A) Wegener interpreted the matching shapes of Africa and South America as evidence of continental drift (reproduced with permission from Hamblin [1994, Figure 16.2]). (B) Hutton interpreted the geometry of this and similar unconformities as evidence that there had been a long gap of time during which erosion had occurred (from http://www.geos.ed.ac.uk/undergraduate/field/siccarpoint/closer.html, downloaded October 2002.). (C) Micropaleontologists interpret the shapes of these planktonic microfossils as evidence of the water temperature in which the fossils grew (reproduced with permission from Kennett [1982, Figure 16.1]). (D) Pitman interpreted the shape of this Eltanin-19 magnetic anomaly profile across the Pacific-Antarctic Ridge as evidence of seafloor spreading (adapted with permission from Pitman and Heirtzler [1966, Fig. 3]).

mentologists use the presence of ripples and certain other sedimentary structures to infer that a sedimentary stratum was deposited under flowing water, and use the orientation and asymmetry of the ripples to determine which way the current was flowing in the ancient body of water (Blatt et al., 1972). Whether a river is meandering, straight, or braided speaks to a geomorphologist about the energy regime, discharge, and slope of the river (Allen, 1970). Similarly, the grain size distribution of sedimentary particles tells a sedimentologist about the velocity of an ancient river; it takes a higher energy flow to carry gravel than sand. Sedimentary stratigraphers infer whether sea level was rising or falling on a continental margin from the shape of the sedimentary "packets" in seismic-reflection profiles acquired perpendicular to the margin (Vail et al., 1977).

The symmetry or lack of symmetry of an object of nature can be attributed to either the properties of its constituents or to the circumstances under which it formed or evolved. The symmetry of crystals emerges from the packing geometry of their constituent molecules. Animals that move are likely to have evolved bilateral symmetry, with sensors (e.g., eyes, nose) located on the side that first encounters new stimuli, whereas organisms with radial symmetry are more likely to be attached to the seafloor, equally ready to cope with threats or opportunities coming from any direction.

To summarize from these examples, the shape of a natural object can be influenced by its strain history, the energy regime under which it was formed, the chemical environment under which it formed, and changes in the physical or chemical environments that it experienced after its initial formation. Geoscientists seek to reason backward from observing the morphology to inferring the influencing processes, guided by observations of current-day processes that are thought to be analogous. Key questions involved in this task are: What processes or forces could have acted upon this mineral or landform or fossil or organism (the fossil before it died) to cause it to have this shape? What function could this form have served in the life of the organism?

Geoscience novices, like novice learners in other disciplines (e.g., Chi et al., 1981), generally begin by applying learned rules of thumb, without necessarily understanding the underlying causal relationship. At the expert level, the process of inferring history and formative processes involves reasoning from first principles about the connections among form, function, and history, on the basis of an expert knowledge base about the normal characteristics of the class of objects under study.

### *Insights from the Cognitive Science Literature—Schema Theory*

To explain the organization of knowledge of more complex relations and structures, beyond simple object concepts, schema theory was proposed. A schema is a general knowledge structure that is composed of various relations, events, agents, actions, and so on. People apply a schema to a specific situation to guide their behavior and understanding. In other words, open "slots" in a generic schema are filled out according to specific situations. One of the earliest concepts of schema can be found in Bartlett's (1932) study of the role of expectations in remembering. He told a North American Indian folk tale, which was not familiar to people in the European culture, to English participants, and asked them to recall it later. He found that they did not remember the story as it was, but changed or "reconstructed" it so that it became more consistent with traditional European folk stories. That is, their interpretation of the story was influenced by their expectations, or schemata.

Thus if a geoscientist or geoscience student has a schema that says "sedimentary rocks are deposited in layers," that person will tend to see layers when observing sedimentary rocks in the field, and will tend to recall layers when describing that outcrop at a later time.

It should be noted that cognitive scientists consider the process of understanding to be a two-way, constructive process; that is, understanding is influenced by existing knowledge structures, and at the same time, the knowledge structures undergo changes in interaction with the world. Piaget called these processes assimilation and accommodation, where assimilation refers to integrating new information into one's existing schema, and accommodation refers to modifying one's schema in light of new information. He argued that knowledge was acquired in interaction between the self and the world, and "the progressive equilibrium between assimilation and accommodation is an instance of a fundamental process in cognitive development" (Piaget, 1983, p. 109).

How do geoscientists develop expert schemata for ascribing meaning to the shape of natural objects? This is a very interesting but underinvestigated issue. We offer two generalizations. A first generalization is that a new explanatory schema in geosciences may originate by observing instances when the formative process and the resulting objects can be observed simultaneously, either in a modern environment or in an experiment. For example, the schema for inferring paleocurrent directions in ancient sedimentary rocks from the shape and orientation of preserved sedimentary structures, was constructed by observing ripples and other bedforms in modern bodies of water where the current speed and direction can be measured directly. Similarly, schemata for interpreting metamorphic rocks are informed by laboratory experiments in which rocks are deformed under elevated temperatures and pressures. This method of developing new schemata is enshrined in the geologist's slogan: "the present is the key to the past."

A second generalization is that a new explanatory schema in geosciences may originate by observing fortuitous instances in which the shape of the natural object is a nearly pure result of one formative process. For example, the schema for interpreting the shapes of wiggles in profiles of the magnetic signature of the oceanic crust in terms of seafloor spreading, was clinched by Walter Pitman's interpretation of the Eltanin-19 profile (Glen, 1982; Pitman and Heirtzler, 1966). This beautifully symmetrical profile has a high-latitude position, E-W orientation, and location away from ridge jumps and transform offsets, which lead to a simple, clear profile shaped only by seafloor spreading (Fig. 3D). Later workers expanded the schema to cover situations where the magnetic signal was weaker or obscured by other processes. This second anecdote illustrates something else about the development of schemata in science: Piaget's cyclical process of assimilation and accommodation can be shared across a community of investigators rather than occurring entirely within one brain.

## Recognizing a Shape or Pattern amid a Noisy Background

### *The Geoscientist's Task—Finding Meaningful Patterns or Shapes in Image Data and Outcrops*

Quantitative, digital geophysical data are often displayed as images rather than numbers. Examples include seismic-reflection profiles, side-looking sonar data, and satellite remote-sensing data. This strategy of transforming the numbers of quantitative data into something that looks like a picture is a matter of preference. For example, bathymetric and topographic data have historically been shown as contour maps, a form of data display that preserves the numerical depth or elevation (Fig. 4A). With the availability of increased computer processing power, marine geologists and geomorphologists now often choose to display bathymetric and topographic data as shaded-relief images, a form of display that looks somewhat like a photograph and does not present the absolute depth or elevation as a number (Fig. 4B).

Why should the developers of geophysical instruments strive to acquire the most accurate and precise digital data, but then transform these numbers into picture-like data displays before interpretation? It seems that image displays allow the data interpreter's eye and brain to tap into a powerful ability to recognize significant patterns amid noise. The eye can "see" erosional or faulted fabric in the shaded-relief display more easily than in a contour map or other numerical display. This ability to detect geologically significant patterns improves through training and practice. An experienced interpreter of seismic-reflection data can confidently and reproducibly trace seismic reflectors across a profile that looks like uniform gray noise to the untrained eye.

The ability to spot subtle but significant patterns amid a visually complex background is crucial on the outcrop as well. A talented paleontologist can stand at an outcrop with a bus-full of other geologists and spot fossils where the others see nothing.

In recognizing a shape or pattern amid a noisy background, the expert geoscientist's eye is guided by experience of what might be important. For example, in spectroscopic studies, an expert would recognize significance in asymmetry of peaks, for example, a "shoulder" on a peak that might indicate absorption of a given wavelength or overlapping peaks that have to be deconvolved. Geoscience novices describing the same data set might not even notice the asymmetry, because it conveyed no significance to them.

### *Insights from the Cognitive Science Literature—Expert Problem Solving*

Although the geoscientist interpreting an outcrop or image may be tapping into a universal human ability to see patterns amid visual clutter, it seems that expert geoscientists can see significant patterns where novices do not. What differentiates experts from novices? It has been found that experts do not simply have more factual knowledge, but they also store and use knowledge in more meaningful and efficient ways than do novices. For example, Chase and Simon (1973) found that chess masters recalled briefly presented board positions from actual games better than novice players, whereas the two groups of players did not differ in the accuracy of recall when the pieces were randomly arranged on the board. Gilhooly et al. (1988) found that undergraduate students skilled in reading topographic contour maps showed better memory for contour maps than low-skill students, whereas the two groups of students did not differ in accuracy of memory for ordinary town maps. Lesgold et al. (1988) found that, in diagnosing X-ray films, expert radiologists were superior to novices in clustering observed abnormalities into a single medical problem and generating diagnostic hypotheses. In each case, the experts were attuned to patterns in visually perceived information because those patterns had significance for them, significance that the novices were not aware of. In such expert problem solving, past experience and existing knowledge should play an important role (as discussed in the section on schemata).

### *Insights from the Cognitive Science Literature—The Embedded Figures Test*

The embedded figures test is a classic psychometric test, often given as one of a battery of tests designed to assess people's spatial abilities. In this test, the participant is shown a simple shape, and then asked to find and trace that simple shape where it occurs within a more complex configuration (Fig. 5A). The specific ability required by this test is to perceive and keep an image in memory and then detect it among complex configurations by ignoring irrelevant or distracting information (called flexibility of closure; Carroll, 1993).

Although the embedded figures test resembles the geoscientist's task of finding reflectors in a seismic profile or fossils in an outcrop or structures in a geologic map (Fig. 5B), there are significant differences that make the geoscientist's task harder. First, in the embedded figures test, the example simple figure and the embedded simple figure are exact duplicates with respect to size, shape, and orientation; in contrast, the simple figure in the geoscientist's tasks can be regarded as an archetype or model, which could differ in size or orientation or details of morphology from the embedded figure. Second, in some variants of the embedded figures test, one can look back at the simple figure while searching within the complex figure; whereas the geoscientist is typically comparing against a mental picture of the sought-after shape rather than against a physical object or external representation. Also, in the embedded figures test, one knows that the simple shape is, in fact, present in the complex shape, but the geoscientist has no such assurance. Finally, the background within which the geoscientist is searching is often much more complicated and noisy than the "complex" figure of the embedded figures test.

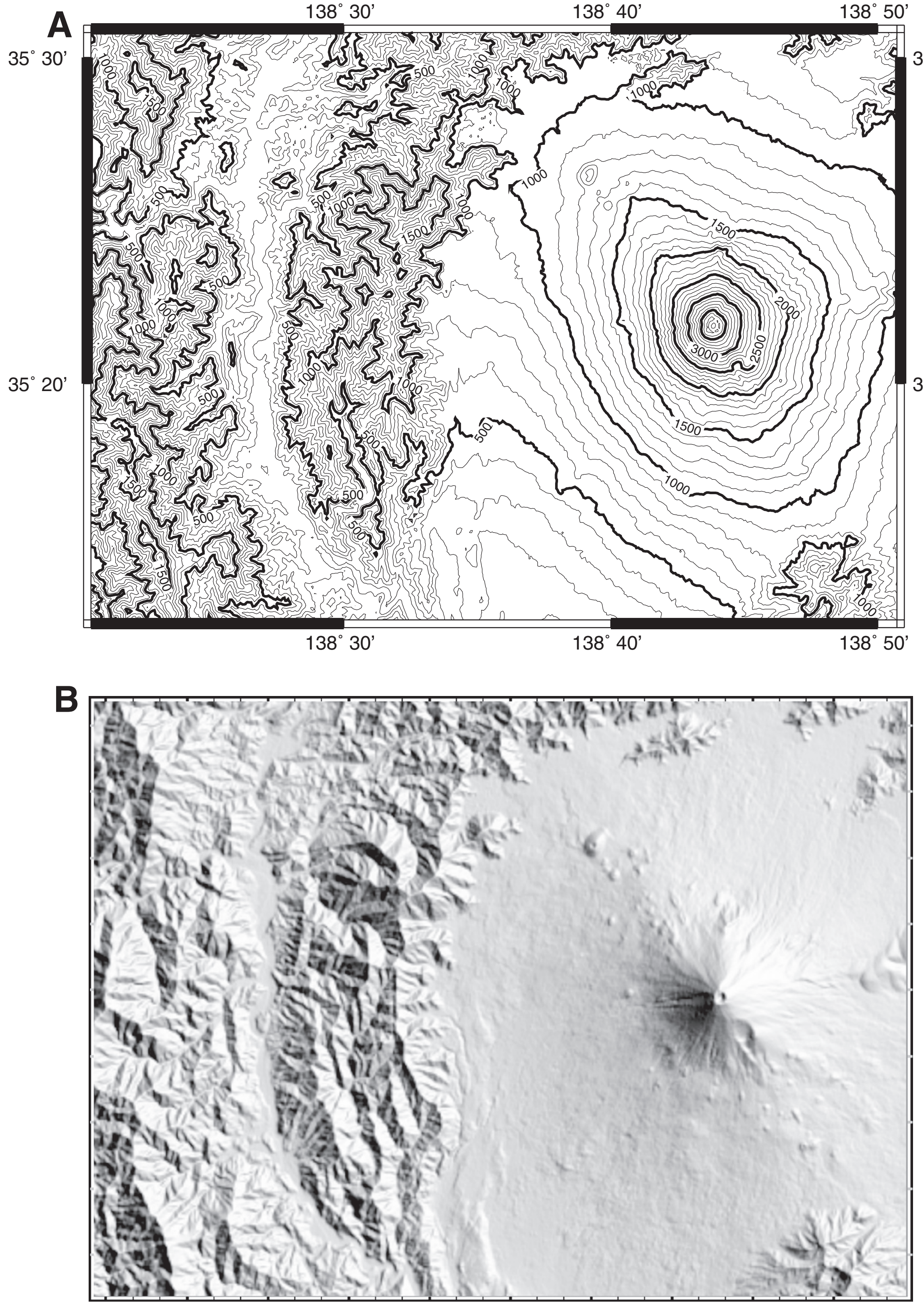
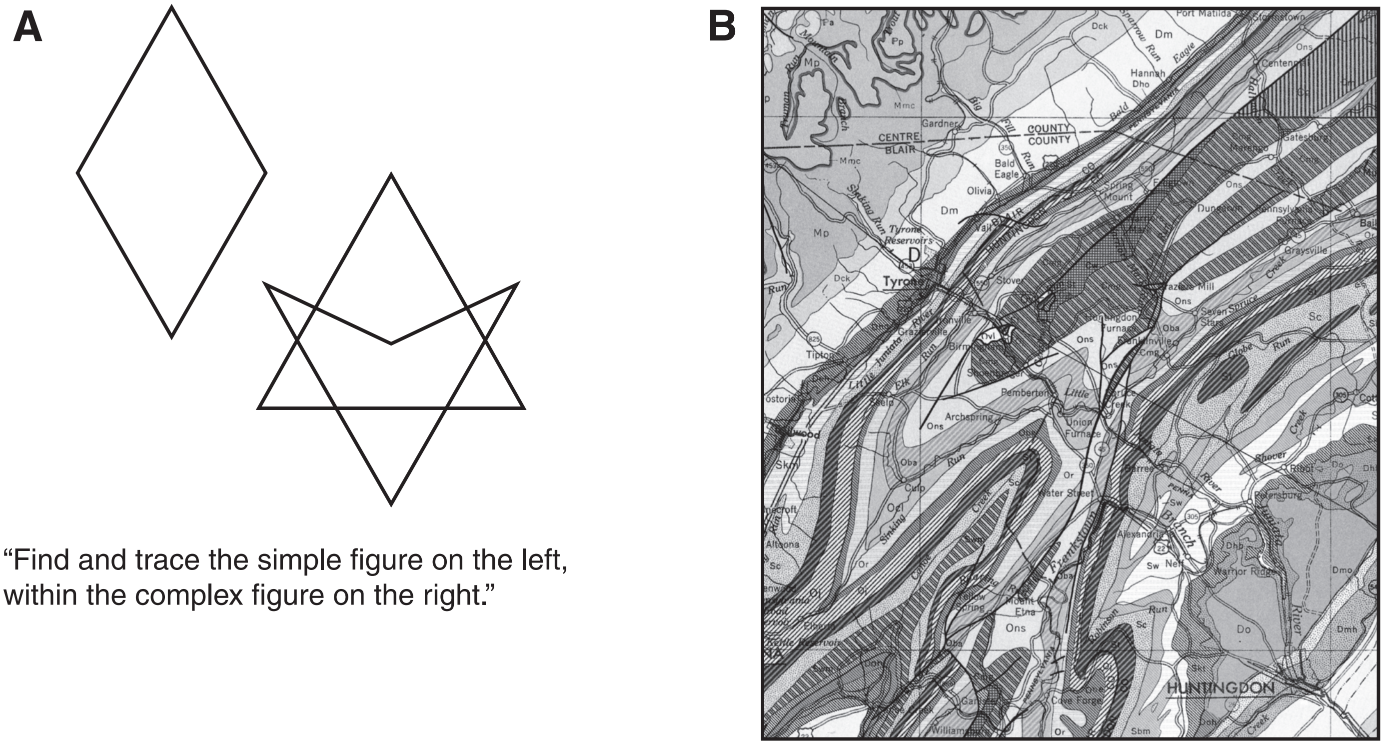


Figure 4. For certain types of data, a numerical, quantitative display may be less informative than a display that mimics what the human eye is used to seeing in the world around us. (A) Topography in the region of Mt. Fuji, Japan, shown as contours in meters. (B) The same elevation data, shown as a shaded-relief image. The topographic contours retain the quantitative information about the elevation of each point on the map. However, most geoscientists find it easier to infer the erosional and volcanic processes that shaped the landscape by examining the shaded-relief image display. (Images created by William Haxby using GeoMapApp.)



“Find and trace the simple figure on the left, within the complex figure on the right.”

Figure 5. (A) The embedded figures test requires the participant to find a simple figure or drawing embedded within a more complicated figure (reproduced with permission from Eliot and Smith [1983, p. 409]). (B) The geoscientist exercises a similar skill looking for significant shapes or patterns in a complex geologic map or in image data. On such a geologic map (original in color), the color bands represent rock units of different ages. The zigzag pattern of the rock units in the SW quadrant of this map is characteristic of folded rock strata that have been partially eroded (reproduced with permission from Owen et al. [2001]).

The relative ease with which experts “see” fossils or seismic reflectors leads us to wonder whether embedded-figures performance would be dependent on the familiarity of the shape being sought. Are arbitrary shapes harder for people to find than familiar shapes, such as the household objects and items of clothing typically found in children’s “find-the-hidden-objects” puzzles? If so, that might suggest that the progression from novice to expert in geoscience tasks that involve recognizing a significant pattern or shape amid a complex or noisy background is driven by the progression from unfamiliarity to familiarity with the sought-after shapes or patterns. In fact, there have been research findings that show the effects of familiarity on the speed of detecting embedded figures: Hock et al. (1974) found that, within embedded complex figures, uppercase alphabet letters in their normal orientation were detected faster than letters in unfamiliar orientation (rotated 180°). Hanawalt (1942) also found that practice facilitated people’s detection of embedded figures.

### *Questions for Future Research*

What steps are involved in the progression from novice to expert in the task of finding significant patterns or shapes in a visually complex background, such as an outcrop, geophysical image, or geologic map? How important is exactness/inexactness of fit between the embedded shape and the example shape? How important is being able to see the example shape while looking for the embedded shape? How important is familiarity/unfamiliarity with the sought-after shape?

## COMPREHENDING SPATIAL PROPERTIES AND PROCESSES

### Recalling the Location and Appearance of Previously Seen Items

#### *The Geoscientist’s Task—Remembering Geological Observations*

The great Appalachian field geologist John Rodgers (Rodgers, 2001) knew the location of every outcrop and every ice cream stand from Maine to Georgia. Students recall that he remembered the salient sedimentary and structural characteristics of every outcrop he had ever seen in any mountain range in the world, and where it was located. His ability to remember the relationships among the rock bodies at those outcrops allowed him to construct, over a long lifetime in the field, a mental catalog of occurrences of geologic structures, which he drew upon to create a masterful synthesis of how fold-and-faulted mountain ranges form (Rodgers, 1990).

William Smith [1769–1839] made the world's first geologic map, a map of England and Wales showing rocks of different ages in different colors (Winchester, 2001). When Smith began his field work, it was not understood that rocks occurred on Earth's surface in organized spatial patterns; he figured out that the organizing principle was the age of the rocks as recorded in their fossils. Many spatial skills must have contributed to Smith's effort, but among them was his ability to remember and organize, aided only by the simplest of paper-and-pencil recording aids, a huge body of spatially referenced observations. His nephew, John Phillips, wrote of William Smith: "A fine specimen of this ammonite was here laid by a particular tree on the roads side, as it was large and inconvenient for the pocket, according to the custom often observed by Mr. Smith, *whose memory for localities was so exact* that he has often, after many years, gone direct to some hoard of nature to recover his fossils" (cited in Winchester, 2001, p. 270; emphasis added). The ammonite example focuses on memory for the location of a discrete object, but geologists must also have a memory for recurring patterns or configurations, for example, a distinctive sequence of rock types.

### *Insights from the Cognitive Science Literature—Object Location Memory*

In the psychometric literature, males have been found to perform better than females on some spatial tests, including the mental rotations test, which will be described later (see Linn and Petersen, 1985; Voyer et al., 1995). However, performance on one spatial task has been found to favor females: object location memory task. In this task, the participant is shown an array of objects and, after removal of the array, asked to recall what objects were located where. For example, Silverman and Eals (1992) showed participants an array of objects; after removing the array, they showed the participants a new array of objects, saying that the two arrays contained the same objects. The participants' task was to identify which items were in the same location and which were not. Whether the learning was incidental or intentional (i.e., whether they were explicitly instructed to remember the array or not), females recalled more objects correctly than males did. Another test for this ability is the board game Memory, where people have to remember under which card a specific picture occurred when a matching picture is overturned on another card (McBurney et al., 1997). Some researchers have interpreted these findings from an evolutionary perspective, arguing that in a hunter-gatherer society, object location memory was important for female foragers, who needed to remember the location of medicinal and edible plants so as to be able to harvest them at a later date. For a discussion about the rationale of evolutionary psychology, see Tooby and Cosmides (1992).

Siegel and White (1975) described a special kind of figurative memory, called "recognition-in-context" memory, which allows one to remember not merely "I have seen that before," but also what the landmark was next to, when it last occurred, and what its connection was to other landmarks. Siegel and White state that the clarity of a recognition-in-context memory depends in part on the degree of meaningfulness of the event for that person at that moment. This suggests that, within an individual's education and career in geosciences, spatial memory for Earth features should strengthen as he or she develops the contextual and theoretical framework to establish "meaningfulness" for isolated observations. However, it does not explain the person-to-person variability between spatial geniuses, such as Rodgers or Smith, and ordinary geoscientists.

## Describing the Position and Orientation of Objects

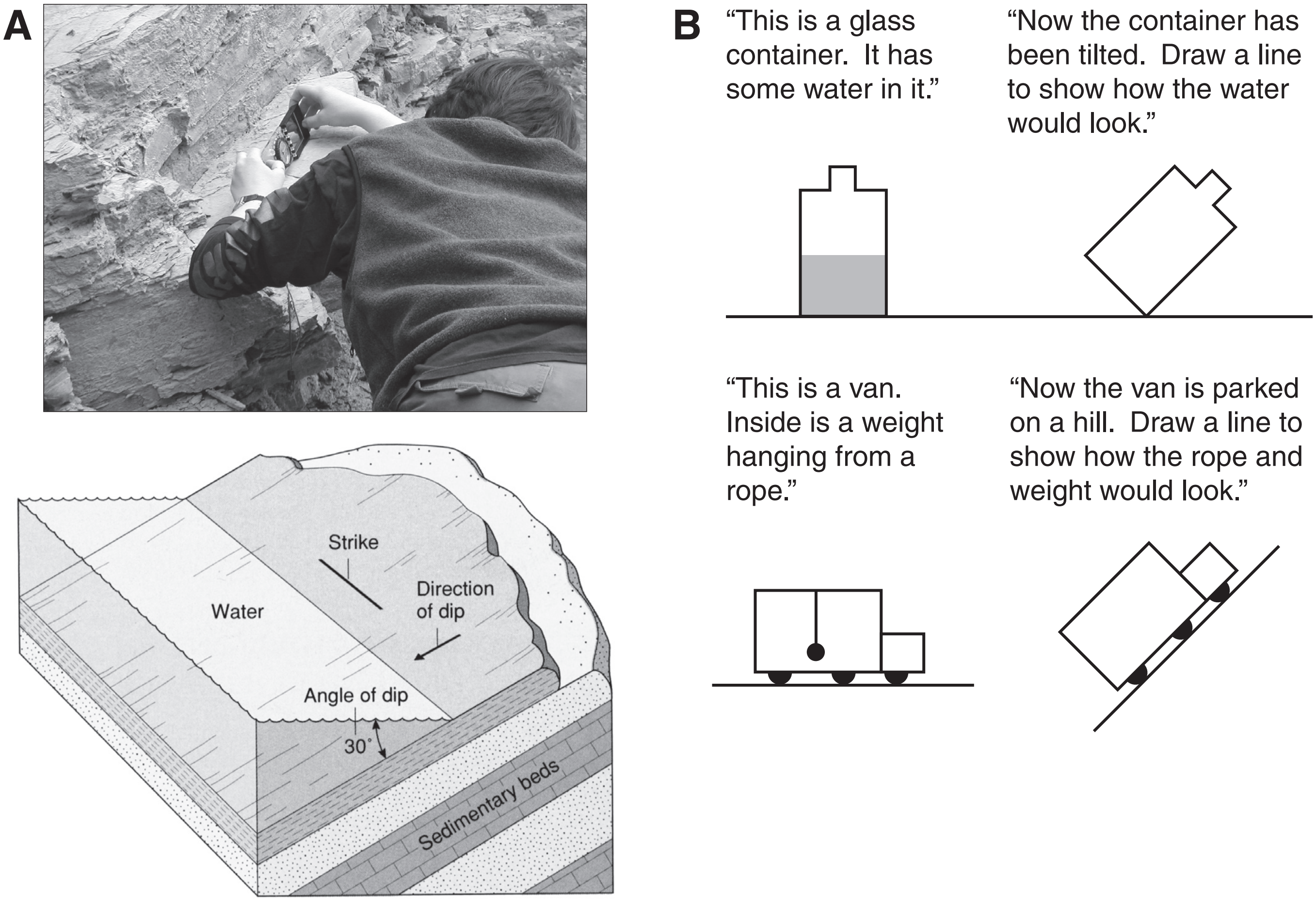
### *The Geoscientist's Task—Describing the Position and Orientation of Real-World Objects Relative to the Earth*

Learning to measure strike and dip of sedimentary strata or other planar surfaces is a well-known stumbling block for introductory geoscience students (Fig. 6A). Strike is the compass azimuth of the line defining the intersection between the surface to be described and the horizontal plane. Dip is the angle between the horizontal plane and the surface to be described, measured within a vertical plane perpendicular to the strike line. Strike and dip measurements can be made in the field with a geologist's compass. These two measurements together uniquely define the orientation of a planar surface relative to the Earth. Many students seem to have trouble grasping this technique at any kind of deep or intuitive level.

Until the advent of full-time-available global positioning system (GPS), navigation was a huge issue for seagoing oceanographers. The quality of field work at sea depends on oceanographers' ability to accurately determine the latitude and longitude of ships, sampling devices, and instruments. Every navigation technique—dead reckoning, sextant, Loran, transit satellite navigation, seafloor-based acoustic transponders, or GPS—requires thinking about how angles and/or distances change as a function of relative motions between objects. By knowing the positions of several objects (e.g., satellites, stars, seafloor acoustic transponders) in an frame of reference fixed onto the rotating Earth, the navigator can determine the unknown position of the object of interest. Seismologists face a similar problem when using information about the distance of an earthquake from known seismograph stations to triangulate the unknown location of the earthquake.

### *Insights from the Cognitive Science Literature—The Water-Level Task*

Piaget and Inhelder (1948 [1967]) developed the water-level task and plumb-line task to investigate children's understanding of vertical and horizontal axes, which they considered to be a Euclidean spatial concept (Fig. 6B). The water-level task asks the participant to draw the surface of water inside a drawing of a bottle tilted at various angles from the tabletop; the plumb-line task asks the participant to draw a weighted string (i.e., a plumb



"This is a glass container. It has some water in it."

"Now the container has been tilted. Draw a line to show how the water would look."

"This is a van. Inside is a weight hanging from a rope."

"Now the van is parked on a hill. Draw a line to show how the rope and weight would look."

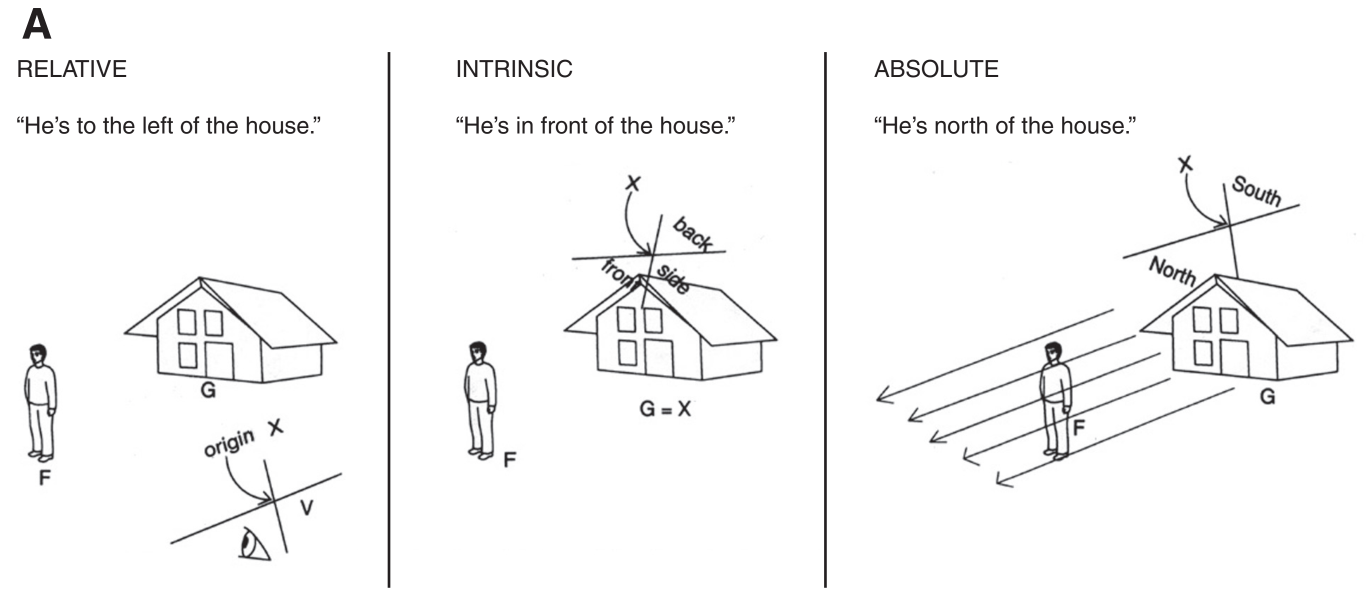
Figure 6. (A) Geologists record the orientation of a sloping planar surface by measuring the strike and dip of the surface, which requires measuring relative to an imaginary horizontal plane and within an imaginary vertical plane (photo by Kim Kastens; figure reproduced with permission from McGeary and Plummer [1998, Figure 6.8]). (B) Psychologists use the water-level and plumb-line tasks to assess people's understanding of the horizontal and vertical axes (adapted with permission from Vasta et al. [1996, Figures 1 and 3]).

line) hanging from the top of the tilted bottle (or, in later investigators' versions, from the roof of a van on a hillside). These tasks resemble the geologist's measurement of strike and dip. In fact, one introductory textbook illustration (McGeary and Plummer, 1998) seeks to clarify the meaning of the term strike by showing imaginary water lapping against the planar surface to be described; the imaginary shoreline defines the line of intersection between the horizontal surface and the surface to be described, that is, the strike line (Fig. 6A). Piaget and Inhelder found that, at an early developmental stage, children did not grasp the notion of horizontal/vertical at all, then, as they got older, began to draw straight lines that were parallel to the base of a bottle, and finally came to understand that the water level should be horizontal and the plumb line should be vertical at any degree of tilt.

More recent investigators have reported that a significant portion of college students, particularly female students, have trouble with these tasks (e.g., Liben, 1978; Liben and Golbeck, 1984; Thomas and Jamison, 1975; Thomas et al., 1973). It has also been pointed out that the relevant physical knowledge about the behavior of water in the real world and a fully developed conceptual framework of space are important for these tasks (e.g., Liben, 1991; Merriwether and Liben, 1997; Vasta et al., 1996). It seems likely that a college student who struggles with the water-level task would be bewildered by dip and strike.

### *Insights from the Cognitive Science Literature—Frames of Reference*

To describe an object's position or orientation, one needs to specify it with respect to something else; that is, one needs to define location in a frame of reference. Levinson (1996) identified three kinds of frames of reference (Fig. 7A). In a relative frame of reference, positions are specified in terms of directions relative to a viewer (e.g., the cat is to the left of the tree; the coarse-grained sediments are at the right end of the outcrop). Distance from a viewer is also a form of relative positional information (e.g., the cat is near to me; the earthquake is 152 km from the seismograph). In the latter example, the "viewer" is not a human being, but rather a scientific instrument that observes Earth on



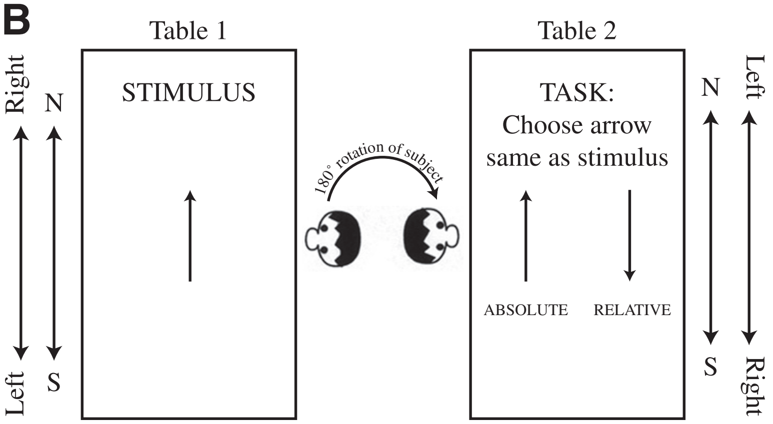


Figure 7. (A) Levinson (1996) discussed three types of frames of reference: relative, intrinsic, and absolute (F—figure; G—ground; V—viewpoint; X—origin of the coordinate system). The coordinate axes are attached to the viewer (V) in the relative frame of reference, to the house (G) in the intrinsic, and to the Earth in the absolute. Seismologists locating earthquakes and oceanographers navigating remotely operated vehicles and submersibles must translate between measurements relative to the observation point (e.g., distance from earthquake to seismograph or distance from bottom-moored navigation beacon to submersible) and positions in an absolute frame of reference (latitude, longitude, depth). (B) Dutch and Tenejapan participants were shown a stimulus arranged in a specific direction on one table, and then asked to rotate 180° and choose on another table the one which they thought was the "same" as the one seen before (reproduced with permission from Levinson [1996, Figures 4.2 and 4.9]).

behalf of the human scientist. In an intrinsic frame of reference, positions are specified in terms of inherent properties of an object within the system under consideration (e.g., the cat is in front of the car; the cracks are along the axis of the fold). Oceanographers and other seafarers use port and starboard to establish an unambiguous intrinsic frame of reference to replace the ambiguous relative terms left and right. An absolute frame of reference is an arbitrary frame fixed onto the surroundings, outside of the system under consideration. Cardinal directions (north, south, east, and west) and latitude and longitude are absolute frames of reference fixed onto rotating Earth.

Developmentally, it has been shown that the frame of reference that children use progresses from an egocentric (or self-centered) frame of reference to an absolute (allocentric or environment-centered) frame of reference (see e.g., Hart and Moore, 1973). Children first orient objects in space with respect to their bodies, namely, they use an egocentric frame of reference. The egocentric frame of reference is a special case of the relative frame of reference, in which the viewer and the speaker coincide. Children at a later stage of development are able to interrelate objects in space in a coordinated frame of reference. Acredolo (1976, 1977), in a series of experiments, showed that younger children (three-year-olds) relied on the relationship with their own bodies in locating an object in space. For example, once trained to find an object to their left, they went to the wrong location—to their left—after being rotated 180° and starting from the opposite side of a room. In contrast, older children (five-year-olds) comprehended the reversal with respect to their bodies and also used landmarks to locate an object in a fixed, larger frame of reference.

One interesting and important finding about the use of different frames of reference is that they are not equally accessible to humans. When the relative and absolute frames of reference are compared, many people find the latter more difficult to use. A major reason for the difficulty is that, to use the absolute frame of reference, one needs to constantly update one's own orientation relative to the surroundings (e.g., if you head to the north and make a right turn, your right becomes south, not east). In contrast, in the relative frame of reference, one's right is always right regardless of rotation. Also, Levinson (1996) found cultural influences on the choice of frame of reference: the characteristics of language that people use affect the use of different frames of reference in nonlinguistic tasks. He compared two groups of people, Dutch and Tenejapan. Dutch speakers predominantly use relative terms in referring to directions, such as front, back, left, and right; whereas Tenejapan speakers use absolute terms, such as downhill (corresponding to north in their local terrain) and uphill (corresponding to south) in conversation. Levinson presented them a stimulus arranged in a specific direction on one table, and then asked them to rotate 180° and choose on another table the one that they thought was the "same" as the one seen before (Fig. 7B). If they encode the stimulus in the relative sense, they should choose the one heading to their right as the same; if they encode the stimulus in the absolute sense, they should choose the one heading to the north as the same. Dutch participants predominantly showed the former response pattern, whereas the Tenejapan participants tended to show the latter response pattern.

The oceanographer's navigation tasks require conversions between relative and absolute frames of reference. Most navigation techniques generate observables in a relative frame of reference: celestial navigation measures the angle between a star and the horizon as seen from the navigator's vantage point; dead reckoning measures (or estimates) the distance that the navigator has traveled relative to a previous navigation fix; GPS measures the distance between the satellite and the receiving antenna; acoustic transponder navigation measures the distance between a ship or instrument and the transponder, and so on. But what the navigator desires is a position in an absolute frame of reference: latitude, longitude, and in the case of a submerged vehicle, depth. Similarly, seismologists who seek the location of an earthquake work initially in relative frames of reference, as they calculate the distance from epicenter to several seismographs, and then translate this data to an absolute frame of reference to report their findings as latitude, longitude, and depth.

### *Question for Future Research*

What are the mental processes involved in visualizing the transformation of positions and orientations from one spatial frame of reference to another, as for example triangulating to convert earthquake location data out of the relative distances from seismic stations into the absolute framework of latitude, longitude, and depth?

## Using and Making Maps

### *The Geoscientist's Task—Using Maps to Record and Convey Spatial Information*

Almost all subdisciplines of geosciences use maps to record and convey information about the Earth. Maps are used to document the locations of discrete phenomena such as ore deposits or volcanoes, or the distribution of properties such as the geologic age of rocks, the salinity of seawater, or the temperature of the atmosphere. Maps capture a record of ephemeral phenomena such as earthquakes or weather systems. Geoscientists use maps to show the past (e.g., reconstructions of previous plate tectonic geometries), the present (e.g., geologic maps), and the future (e.g., climate forecast maps). Maps are most often used to record and convey information that the map maker considers to be factual or at least consistent with available data, but they can also be used to convey a hypothesis, for example Wegener's (1929) hypothesis of continental drift.

For generations of geology students, the field-mapping course has been a rite of passage. In such a course, students observe rock outcrops in the field, make measurements of characteristic attributes, record information about the age, lithology, and structure of observed rocks onto a topographic base map, and then interpret their observations in terms of buried structures and their formative processes. Because the spatial relationship among observations is crucial in inferring buried structures, students must become proficient in locating themselves on the topographic base map by comparing observed features of the terrain with features on the map. Many students find this task difficult.

Learning how to figure where you are on a topographic map has a counterpart in ordinary life in figuring out where you are on a road map or walking map. The mental process involves making connections between the three-dimensional, horizontally viewed, infinitely detailed, ever-changing landscape that surrounds you, and the two-dimensional, vertically viewed, schematic, unchanging representation of that landscape on a piece of paper (Kastens et al., 2001). Although navigating through an unfamiliar terrain by referring to a map is probably the most common map-using task for nonprofessionals, this map skill is rarely taught in school; for example, it is not mentioned in the National Geography Standards (Geography Education Standards Project, 1994).

### *Insights from the Cognitive Science Literature—The Efficacy of Maps as Tools for Conveying Information*

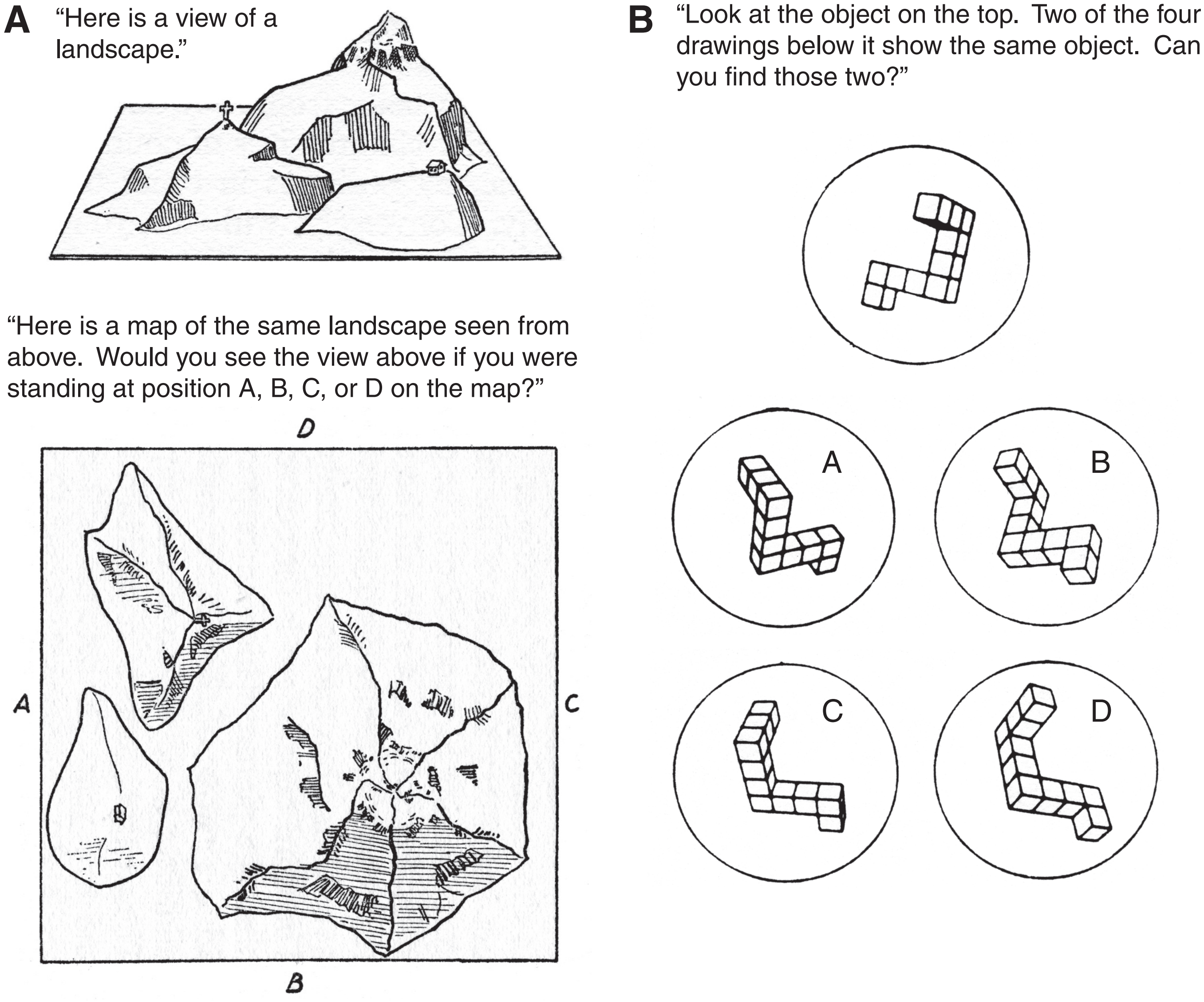
Maps represent information pertaining to space in a schematic and simultaneous fashion. There have been research findings that indicate that the effectiveness of maps and other spatial representations depends on the kind of spatial information being conveyed, the goals or purposes of using such representations, and the spatial ability of users.

Research has shown that maps help people learn the spatial layout of their environment, compared to direct navigation in the space. Thorndyke and Hayes-Roth (1982) examined how two groups of participants' knowledge about a building differed after one group learned the building only by direct navigation and the other group only learned a map of the building. The navigation-learners did better in estimating along-route distances and pointing to unseen landmarks standing at several locations in the building, whereas the map-learners did better in estimating straight-line distances and locating landmarks on a map in relation to each other. Thus, map-learners comprehended the layout of landmarks in the building better than navigation-learners, who had difficulty interrelating separate views into an integrated whole.

More broadly, the effectiveness of spatial representations, such as pictures, diagrams, and animations, has also been studied. Hegarty and Sims (1994) examined how well people comprehend the motion of a mechanical system (a system of belts and pulleys) from a pictorial diagram of the system. They found that people who were poor at mentally visualizing shapes and motions tended to make inaccurate inferences about the motion. Mayer and Sims (1994) gave people visual and verbal explanations of a mechanical system (e.g., a bicycle tire pump), either concurrently (animation and narration together) or successively (animation followed by narration, or vice versa); they then examined the degree of transfer of such acquired knowledge to a new situation. The results showed that people with high spatial ability benefited from the concurrent visual and verbal representations, whereas low-spatial-ability people had trouble connecting the two different modes of representations. In a geoscience education context, these findings suggest that a spatial representation, such as a complex map, that communicates well with other geoscientists and with high-spatial-ability students might not communicate well with low-spatial-ability students.

### *Insights from the Cognitive Science Literature—Perspective Taking*

The field-geology students' task of locating themselves on a topographic map bears some resemblance to Piaget and Inhelder's (1948 [1967]) three-mountain problem (Fig. 8A). Piaget and Inhelder developed this test to examine children's ability



"Here is a view of a landscape."

"Here is a map of the same landscape seen from above. Would you see the view above if you were standing at position A, B, C, or D on the map?"

"Look at the object on the top. Two of the four drawings below it show the same object. Can you find those two?"

Figure 8. (A) Piaget and Inhelder (1948 [1967]) developed the three-mountain problem to examine children's ability to envision a space from different viewpoints (reproduced with permission from Piaget and Inhelder [1967, Fig. 21]). (B) The mental rotation test examines the participant's ability to envision what an object would look like if rotated to a different position (adapted with permission from Eliot and Smith [1983, p. 322]). Both of these skills seem related to the field geologist's task of using a map in a field area. Answers: (A), correct answer is A; (B) correct answers are A and C.

to coordinate spatial relationships from different viewpoints (i.e., the acquisition of projective spatial concepts). They had children view a tabletop three-dimensional (3-D) model of three mountains, which differed in color, size, and an object located at the top (a house, a cross, or snow). In one variant of this task, the children were shown a picture of the mountains as seen from a position around the perimeter of the model. They were then asked to indicate which of the four positions around the model (A–D in Fig. 8A) a wooden doll would have to occupy to take a photograph similar to the view in the picture. To accomplish this task, children had to imagine how the three mountains would look from different viewpoints and compare their imagined view with the picture. Similarly, field-geology students must imagine how the terrain would look from different positions within a two-dimensional map, and then compare the imagined view with the actual three-dimensional terrain surrounding them. Piaget and Inhelder's results showed that children's responses were confined to their own perspectives at first, but as they matured they improved in their ability to discriminate views from different positions.

Geoscience educators have observed that many students have difficulty positioning themselves accurately on a topographic base map, which suggests that perspective taking remains difficult even for many college-age people. The geology student's task is more difficult than the three-mountain problem because the geology student must consider an infinite number of possible positions within the map, whereas the three-mountain study has only four possible positions, all located around the periphery of the tabletop model. As an indication that perspective-taking ability is related to map-use ability, Liben and Downs (1993), using a variant of the three-mountain problem, showed that perspective-taking ability was correlated (about 0.30) with children's ability to show on a map the location and direction of a person standing in a classroom.

### *Insights from the Cognitive Science Literature—Mental Rotation*

The ability to mentally rotate objects has been identified as one of the major spatial abilities (see e.g., McGee, 1979). For example, a standard psychometric test called the mental rotations test asks the participant to compare pairs of object drawings (Fig. 8B) and answer if they are the same except for rotation (Vandenberg and Kuse, 1978). People take more time to respond as the angular disparity in orientation between the pairs of object drawings increases from 0° to 180°, indicating that people in fact mentally rotate the drawings as if they were rotating physical objects in space (Shepard and Metzler, 1971). Performance on this test has been found to show wide person-to-person variability (with males outperforming females on average), and to correlate moderately (correlation of about 0.30) with the ability to learn spatial layout of a large-scale environment (e.g., Bryant, 1982). Kail and Park (1990) found that, after receiving training on the mental rotations test, which consisted of hundreds of trials with feedback on correctness, people came to respond much faster, compared to people without training.

Mental rotation ability should be related to the use of maps in the field, inasmuch as one needs to align a map with the surrounds, either mentally or physically. Kastens and Liben (unpublished data) found that the mental rotations test is a good predictor of fourth graders' ability to place colored stickers on a map to indicate the location of colored flags in a field-based test of map skills. Students with poor mental rotation ability made a characteristic error in which they consistently placed stickers on the east side of the map that should have been on the west side, and vice versa, as though they had gotten turned around. Similar findings have been observed with respect to "you-are-here" maps, located on campus, in a shopping mall, inside an airport, and so on: when the map is posted out of alignment with the surrounding space, for example upside down, people often go in the wrong direction, by erroneously thinking that the upward direction on the map corresponds with the forward direction in the space (e.g., Levine et al., 1982, 1984). These "map alignment" effects have also been found when a map is held horizontally by a traveler's hand (e.g., Warren and Scott, 1993).

### *Questions for Future Research*

Why are maps such a powerful tool for recording, organizing, and conveying information about the Earth? Do maps reflect one of the brain's methods for organizing information? Given that maps are such powerful thought-aids for geoscience experts, why is it that a significant number of geoscience novices have trouble using maps and other spatial representations?

## Synthesizing 1- or 2-D Observations into a 3-D Mental Image

### *The Geoscientist's Task—Visualizing 3-D Structures and Processes from 1-D or 2-D Data*

Many geoscience subdisciplines share the problem that observations are collected in one or two dimensions and then must be interpreted in terms of three-dimensional (or four-dimensional, including time) objects or structures or processes. For example, physical oceanographers measure the temperature and salinity of seawater by lowering an instrument package on a wire vertically down from a ship and recording the temperature, conductivity, and pressure at the instrument. Thousands of such vertical CTD profiles have been combined to create our current understanding of the three-dimensional interfingering of the water masses of the world's oceans. Field geologists examine rock layers and structures exposed above Earth's surface in outcrop, taking advantage of differently oriented road cuts or stream cuts or wave cuts to glimpse the third dimension. From this surficial view, they construct a mental view, or more commonly multiple possible views, of the interior of the rock body.

Seismographs record the acceleration of Earth separately in three directions (up/down, north/south, east/west) as a function of time (Fig. 9A, upper panel). Seismograph records from all over the world are examined to see whether the first motion was toward or away from the site of the earthquake, and this information is combined to define four quadrants of Earth with the same sense of first motion (Fig. 9A, lower-left panel). The results are expressed on a "beach ball" diagram, in which quadrants experiencing first motion away from the earthquake are dark and quadrants experiencing first motion toward the earthquake are white (Fig. 9A, lower-right panel). The geometry of the beach ball conveys the two possible orientations of the fault plane and the two possible directions of fault slip (Anderson, 1986). Although much of this process is now automated, students are still expected to understand this progression from one-dimensional observables to three-dimensional sense of motion, and to interpret the resulting spatial representations.

Marie Tharp, pioneer cartographer of the seafloor, visualized the Mid-Atlantic Ridge rift valley from primitive echo-sounder records (Fig. 9B). Although the data were collected as water depth versus distance along a ship track, the scale and display technique did not allow the raw data to be directly viewed as profiles. Tharp and her assistants measured thousands of water depths by hand, plotted them by hand onto table-sized plotting sheets, combined ship's tracks to draw profiles, and then contoured in map view by hand, or sketched physiographic diagrams. Her vision of a crack running down the middle of the Atlantic became one of the early compelling pieces of evidence in favor of the theory of seafloor spreading and continental drift (Lawrence, 1999, 2002).

The expert's visualization of the parts of the structure that cannot be seen is guided by more than a simple mechanical interpolation between the observed sections or profiles. The physical oceanographer's visualization is shaped by an understanding of gravity and buoyancy, which require that low density water masses will not ordinarily underlie higher-density water masses. The field geologist's visualization is shaped by the understanding that marine sedimentation processes tend to produce layers that are roughly horizontal and roughly uniform in thickness before deformation. The seismologist's interpretation of the beach ball diagram is guided by an understanding of the regional tectonics that may make one of the two possible fault planes more plausible. Marie Tharp's case is interesting because the early Heezen and Tharp maps were published before they or anyone else knew any details about the tectonic and volcanic processes that form the seafloor geomorphology. Their maps in areas of sparse data (the Southern Oceans, for example) are far better than would have been possible by interpolating from data alone (Lamont-Doherty Earth Observatory, 2001). The physical oceanographer and the field geologist in our examples are guided by knowledge of the processes that shaped the unseen parts of the puzzle, but in Tharp's case, she seems to have developed an intuition or "feel" for the seafloor before the formative processes were well-understood, perhaps analogous to the "feel for the organism" ascribed to Barbara McClintock (Keller, 1983).

#### *Insights from the Cognitive Science Literature—Visual Processing from an Image on the Retina*

David Marr (1982) offered a computational theory of visual processing that begins with an image on the retina (Fig. 9C). From intensity changes and local geometric structure in the image, a representation of the two-dimensional image, called the primal sketch, is constructed. The next step is to indicate the geometry and depth of the visible surfaces in the primal sketch, in order to construct a representation called the 2½-D sketch. The primal sketch and the 2½-D sketch are viewer-centered representations. The final step of Marr's sequence is to construct a representation of 3-D shape and spatial arrangement of an object in an object-centered frame of reference. The resulting representation is called the 3-D model representation.

Marr's work points out that each one of us has vast experience of converting (probably in most cases unconsciously) two-dimensional retinal images into mental representations that capture the three-dimensional shape of the objects around us, the objects that we successfully pick up, drive around, and otherwise interact with all day long. It seems likely that this life-long practice of 2-D to 3-D conversion comes into play as geoscientists convert 2-D data displays into 3-D mental representations.

#### *Question for Future Research*

How can we capitalize on this experience to smooth the transition from geoscience novice to expert, with respect to tasks involving the synthesis of 2-D observations into mental images of 3-D structures, and then to interpretations of 3-D processes?

### Envisioning the Processes by which Objects Change Position or Shape

#### *The Geoscientist's Task—Envisioning Deformation within the Solid Earth*

Solid parts of the Earth system may respond to imposed forces by changing their shape, by deforming, by folding and faulting. After struggling to visualize the internal three-dimensional structure of a rock body, the geologist's next step is often to try to figure out the sequence of folding and faulting events that has created the observed structures (Fig. 10A). This task may be tackled either forward or backward: backward, by "unfolding" the folds and "unfaulting" the faults; or forward, by applying various combinations of folds and faults to an initially undeformed sequence of rock layers until a combination that resembles the observed structure is found.

Elements of the solid Earth also change their shape through erosion, through the uneven removal of parts of the whole. Thinking about eroded terrains requires the ability to envision negative spaces, the shape and internal structure of the stuff that is not there any more.

Insights from the Cognitive Science Literature—Envisioning Folding and Unfolding of Paper

The geoscientist's mental folding and unfolding of rock strata resembles the paper folding test used by psychologists to

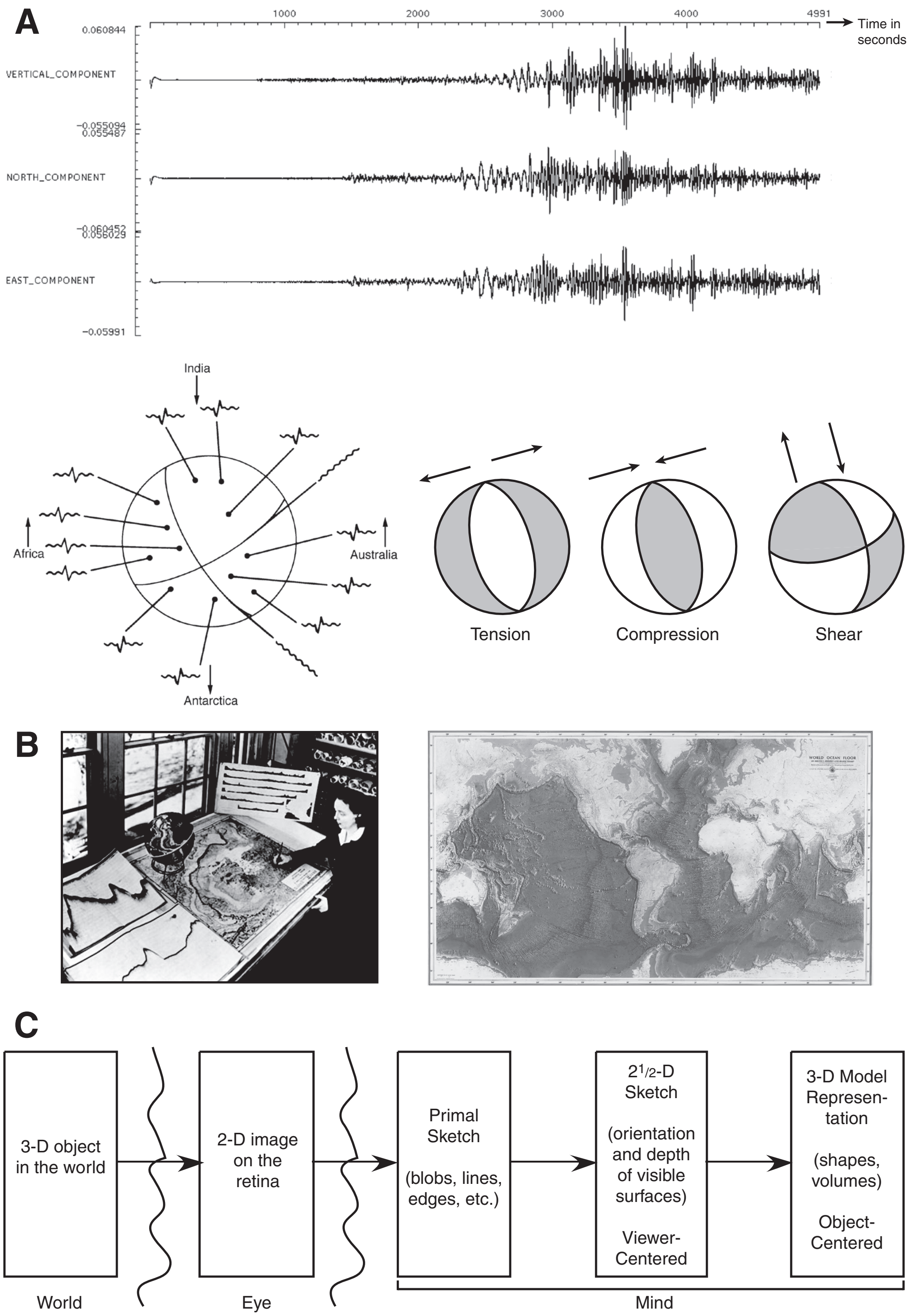
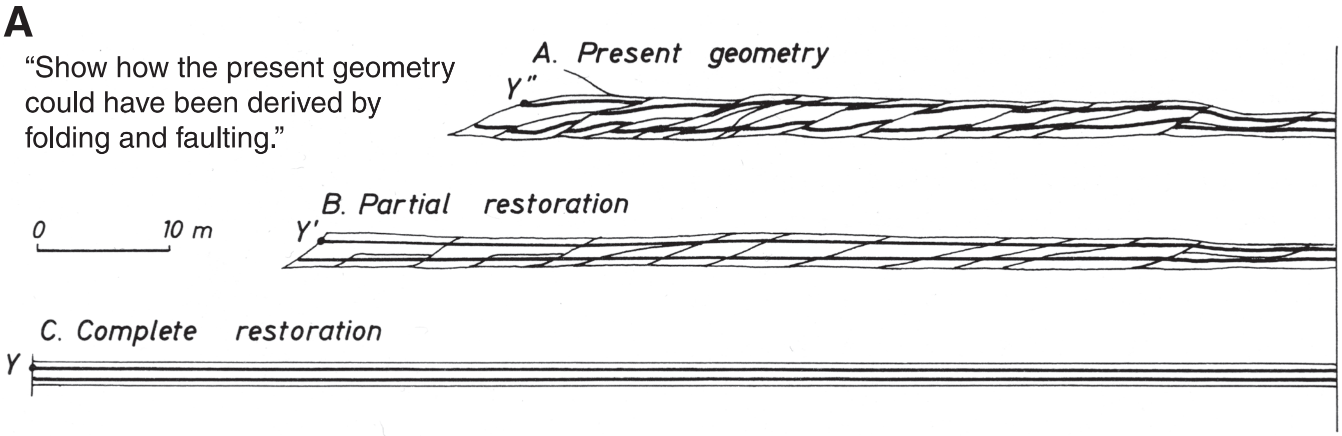
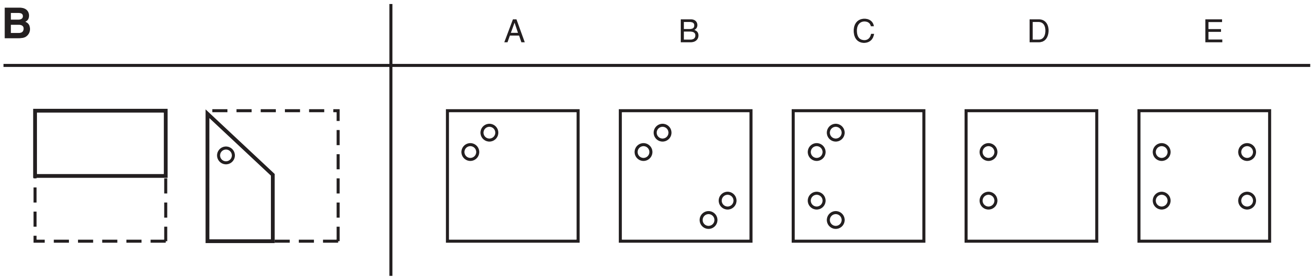


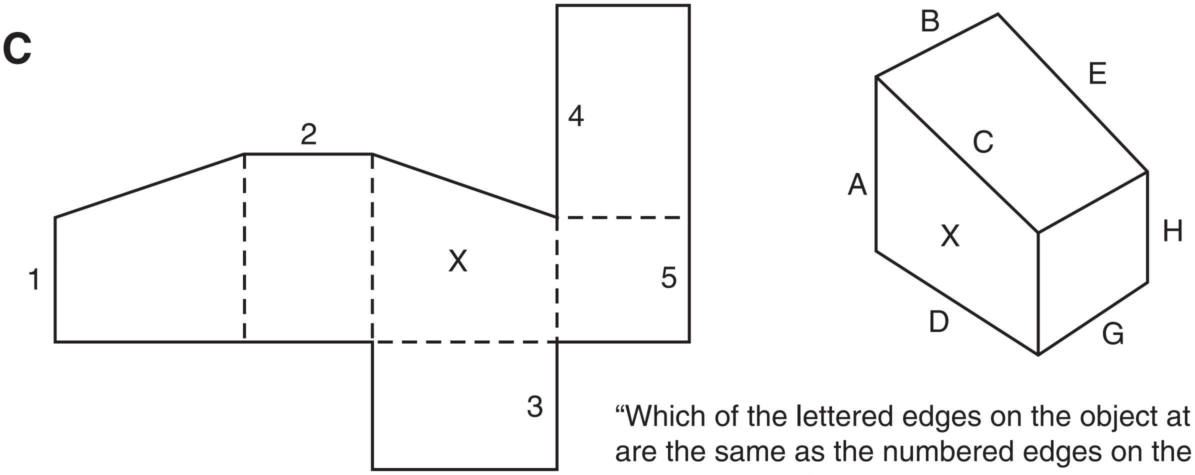
Figure 9. Raw geoscience data, as collected, is often one-dimensional or two-dimensional; it must be integrated to visualize a three-dimensional structure or think about a three-dimensional process. (A) Top: seismograph record showing the acceleration of Earth in three directions (up/down, north/south, and east/west) as a function of time (from Lamont Cooperative Seismic Network Web site, http://www.ldeo.columbia.edu/LCSN/). Lower left: diagram showing Earth divided into four quadrants, each with the same sense of first motion for a specific earthquake. Lower right: "beach ball" diagram, in which quadrants experiencing initial compression are dark and quadrants experiencing initial rarefaction are white (reproduced with permission from Anderson [1986, Figures 3–18 and 3–19]). (B) Pioneering marine cartographer Marie Tharp combined echo-sounder profiles of the seafloor to create physiographic models of the seafloor that allowed both geologists and the general public to visualize the seafloor mountains and valleys as though the water had been removed (photo and map available online at, or linked from, http://www.earthinstitute.columbia.edu/library/MarieTharp.html). (C) David Marr's (1982) model of visual processing illustrates that we all have vast experience transforming information from a two-dimensional image on the retina into a mental representation that captures the three-dimensional nature of a viewed object or landscape.



"Show how the present geometry could have been derived by folding and faulting."



"The two figures on the left represent a square piece of paper being folded. In the second figure a small circle shows where a hole has been punched through all of the thicknesses of paper. Choose a drawing on the right that shows where the holes are after the paper has been unfolded."



"Which of the lettered edges on the object at the right are the same as the numbered edges on the piece of paper at the left?"

Figure 10. (A) Geoscientists need to envision how Earth materials change shape through deformation and removal of parts of the whole. In this example, initially flat-lying sedimentary strata have been deformed by folding and faulting (reproduced with permission from Ramsay and Huber [1987, Figure 24.13]). (B, C) The paper folding test and surface development test assess an aspect of spatial ability having to do with ability to mentally envision the outcome of manipulating an object by folding and unfolding (reproduced with permission from Eliot and Smith [1983, p. 331 and 341]). Answers: (B), correct answer is C; (C), correct answers are 1 = H; 2 = B; 3 = G; 4 = C; 5 = H.

study people's spatial visualization ability (Fig. 10B). This test shows the participant a piece of paper that has been folded and holes punched through all the thicknesses of the paper, and then asks how the paper would look when unfolded. Shepard and Feng (1972) found that people took more time to respond as the total number of squares that would be involved in each fold increased. Kyllonen et al. (1984) showed that performance on the paper folding test can be improved by training, and that the effectiveness of different types of training methods (verbal or visual training, or self-directed practice) depended on both spatial and verbal ability of their participants.

Another related spatial test is the surface development test. In this test, the participant is shown a flat piece of paper and an object drawing. The object can be formed by folding the flat paper on dotted lines (Fig. 10C). The participant is then asked to indicate which edges of the flat paper correspond to which edges of the object drawing. Piburn et al. (2005) found that good performers on this test tended to score high on a geology content exam containing spatial items. Students who took laboratory sessions that emphasized spatial skills in geological contexts using computer-based learning materials (e.g., topographic map reading, sequencing geologic events such as layer deposition, folding, faulting, intrusions, and erosion) scored higher on the surface development test after the laboratory sessions than before. That is, spatial visualization ability seems to be important for geology learning, and also can be improved by spatially demanding geology exercises.

## METAPHORICAL USE OF SPATIAL THINKING

### Using Spatial-Thinking Strategies and Techniques to Think about Nonspatial Phenomena

#### *The Geoscientist's Task—Using Space as a Proxy for Time*

It is fairly common in thinking about the Earth to find that variation or progression through space is closely connected with variation or progression through time. For example, within a basin of undeformed sedimentary rocks, the downward direction corresponds to increasing time since deposition. On the seafloor, distance away from the mid-ocean-ridge spreading center corresponds to increasing time since formation of that strip of seafloor.

As a consequence, geologists often think about distance in space when they really want to be thinking about duration of geologic time. Distance in space is easy to measure, in vertical meters of stratal thickness, or horizontal kilometers of distance from ridge crest. Duration of geologic time is hard to measure and subject to ongoing revision, involving complicated forays into seafloor magnetic anomalies, radiometric dating, stable isotope ratios, or biostratigraphy.

In ordinary life, people also confound lengths in distance and lengths in time, but the asymmetry is the opposite direction. One asks, "How far to New Haven?" and the other answers, "about an hour and a half." In modern society, time is the easy observable; people have more experience at estimating time than distance, and most people wear a time measuring device on their wrists. Therefore, the answer is given in time even though the question is posed in space ("how far?").

Time is important in geosciences because it constrains causal patterns. The sequence in which events happened constrains causality (if A happened before B, then A can have caused or influenced B, but not vice versa). The rate at which events happened constrains the power required (deposition at a rate of meters per thousand years requires different causal processes than deposition at centimeters per thousand years). Using a spatial dimension of a data display as a visual analogy to represent time allows the geoscientist to reveal or highlight causal relationships. For example, Sclater et al.'s (1971) depiction of seafloor age versus depth in oceans of different spreading rates (Fig. 11A) helped reveal the process of lithospheric cooling.

#### *The Geoscientist's Task—Using Space as a Proxy for Other Quantifiable Properties*

Specialists within different branches of geosciences have a tendency to use space as a metaphor for variation in observable but nonspatial parameters of natural systems. For example, petrologists visualize a tetrahedron, in which each corner is occupied by a chemical element or by a mineral of pure composition (e.g., one end member of a solid solution). Any given rock can be placed at a point within the tetrahedron according to the concentration of each of the components in the rock. To communicate this tetrahedron to colleagues, the data are projected down onto one of the sides of the tetrahedron, where it appears on the page as a triangle, with each rock sample appearing as a dot.

Igneous and metamorphic petrologists use pressure-temperature space. The pressure dimension of this space is something like distance beneath Earth's surface, but denominated in units of downward-increasing pressure rather than in units of distance. The temperature dimension is also related to distance beneath Earth's surface, with temperature increasing downward. The chemical composition of an igneous rock depends, in part, on where in pressure-temperature space the initial melt separated out of the mantle.

Physical oceanographers use *T-S* diagrams, where *T* is temperature and *S* is salinity of a water mass (Fig. 11B). Temperature and salinity together control the density of the water mass, and density in turn controls whether the water mass will sink relative to other water masses in the same ocean. Water samples that share a common history will likely cluster together in *T-S* space, and water masses with different histories of formation will usually occupy different areas of *T-S* space.

The mental processes for thinking about these non-distance-denominated "geospaces" feel similar to the thought processes for thinking about distribution of, and movement through, regular distance-space. A clue is that the vocabulary is the same. A body of rock in the mantle "moves" through pressure-temperature space on a "trajectory." Two water masses are "close together" or "far apart" in *T-S* space.

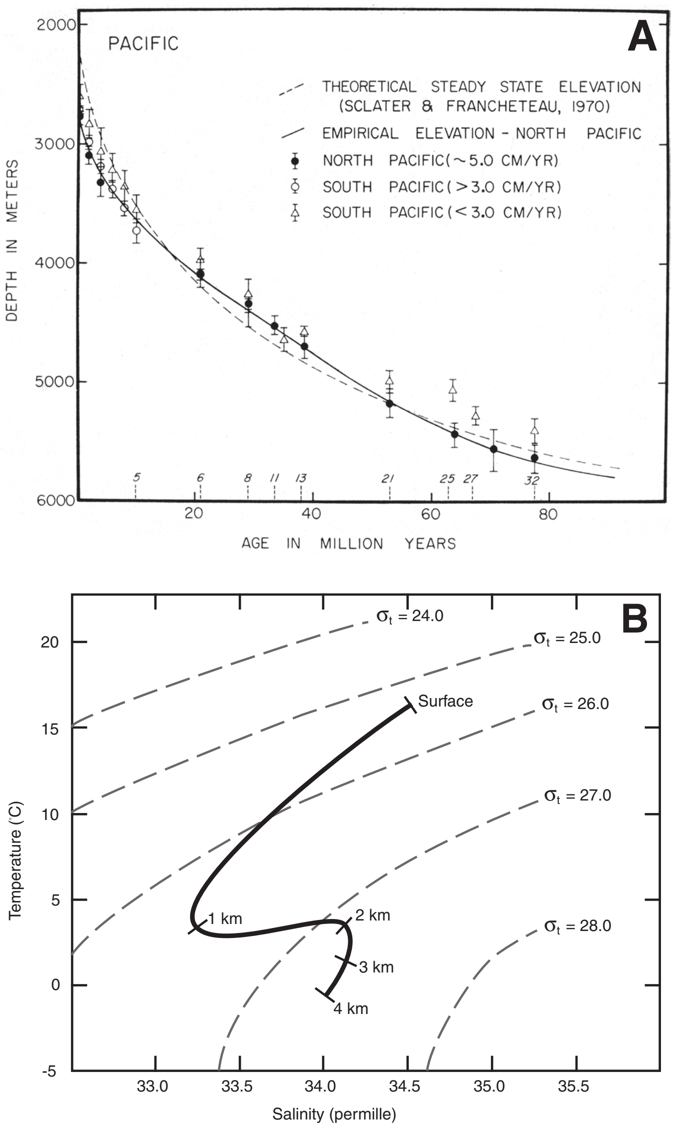


Figure 11. Geoscientists use spatial thinking as a metaphor or mental aid for thinking about nonspatial properties. (A) In this plot of ocean water depth, the horizontal axis represents time, in millions of years, that a patch of the seafloor has spent spreading away from its parent mid-ocean spreading center. When displayed this way, data points from various parts of the world's oceans fall neatly on an exponential curve. If the horizontal axis had been plotted as distance rather than time, the data from oceans with different spreading rates would have been scattered. This spatial-thinking insight helped Sclater et al. (1971) to demonstrate that the oceanic lithosphere cools as it ages, and subsides as it cools (reproduced with permission from Sclater et al. [1971, Fig. 2a]). (B) In this example, spatial dimensions of the graph are used to show temperature and salinity of an oceanic water mass. The dashed lines show contours of constant density, and the solid line shows an idealized vertical profile from sea surface to seafloor, at one spot in the ocean. At this locality, temperature and salinity decrease from the surface down to 1 km depth, temperature stays constant while salinity increases from 1 to 2 km, and then both decrease from 2 to 4 km. Water samples that fall close to each other in temperature-salinity space often share a common history (from online course notes for Climate System, Columbia University, http://eesc.columbia.edu/courses/ees/climate/lectures/o_strat.html).

### *Insights from the Cognitive Science Literature—Spatialization*

Lakoff and Johnson (2003) offered an experientialist account of human understanding, as an alternative to objectivism and subjectivism. They argued that the human conceptual system is metaphorical in nature; in other words, we tend to understand something new in terms of something else, something grounded in our experiences in the physical and cultural environments. We constantly interact with space, and so, according to Lakoff and Johnson, spatialization metaphors are one of our essential ways of understanding. For example, the "more is up" metaphor (e.g., my income rose/fell last year) builds upon the physical basis that "if you add more of a substance or of physical objects to a container or pile, the level goes up" (p. 16). Related "up" metaphors are "future is up" (e.g., What's coming *up* this week?), "good is up" (e.g., he does *high*-quality work), and "virtue is up" (e.g., she has *high* standards), which are based on different aspects of physical and cultural experiences. In this view, use of space for depicting nonspatial parameters, such as those discussed in the previous section, is in line with human understanding of phenomena in general. Using a geoscience example, the geologic time scale, which shows the chronological history of Earth starting from the bottom (pre-Archean) to the top (present), may be conceived of as an analogy of rock layers, as younger strata settled on top of older strata through time.

Siegel and White (1975) discuss humans' tendency to transform nonspatial domains of human experience into a pattern or picture by a spatial interpretation or representation. They provide examples where this spatialization of nonspatial information seems to facilitate memory, retrieval of remembered information, and solution of reasoning problems. In Siegel and White's discussion and examples, the spatialization of nonspatial information is entirely a mental operation, whereas in our geoscience examples, the geoscientist often makes an external representation (e.g., a graph or sketch) in which the two dimensions of the paper or computer screen parallel the inherently nonspatial "dimensions" of the data.

## CONCLUDING REMARKS

### Synthesis: What is "Thinking Spatially" in the Geosciences?

From our discussion of geoscientists' tasks, spatial thinking in the geosciences can be summarized as follows:

1. observing, describing, recording, classifying, recognizing, remembering, and communicating the two- or three-dimensional shape, internal structure, orientation and/or position of objects, properties, or processes;
2. mentally manipulating those shapes, structures, orientations, or positions, for example, by rotation, translation, deformation, or partial removal;
3. making interpretations about what caused the objects, properties, or processes to have those particular shapes, structures, orientations, or positions;

4. making predictions about the consequences or implications of the observed shapes, internal structures, orientations, and positions; and
5. using spatial-thinking strategies as a shortcut, metaphor, or mental crutch to think about processes or properties that are distributed across some dimension other than distance-space.

### Questions for Future Work

Although we have found many fascinating areas of overlapping interests between the domains of geoscience and cognitive science, there are many questions that remain incompletely answered or completely unaddressed. In addition to the finer-granularity questions we discussed above, broader questions include:

1. *Concerning explanatory schemata:* By what steps do geoscience novices learn to use the schemata that will enable them to ascribe meaning to spatial patterns, and how can that process be facilitated by geoscience educators? By what process do geoscientists working at the frontiers of knowledge develop new schemata? How are erroneous schemata replaced?
2. *Concerning evolutionary psychology:* The objects of interest to earth and environmental scientists are the same objects that were of life-and-death importance in the lives of ancestral humans (landforms, bodies of water, rocks, plants, animals). How has the way that the human brain thinks about the Earth and environment been shaped by the evolutionary pressures on our Pleistocene hunter-gatherer ancestors?
3. *Concerning synthesis:* How does the expert geoscientist integrate and synthesize spatial observations into a coherent whole, going from often fragmentary and ambiguous local observations, to a regional or global synthesis of observations, and then to a testable hypothesis about formative processes?

## ACKNOWLEDGMENTS

Kastens originally developed some of the geosciences ideas in this paper for the National Research Committee on “Learning to Think Spatially: GIS as a Support System in the K–12 Curriculum”; she thanks the National Academies staff and the committee members for their encouragement and insights. Some of these ideas were presented at a Pardee Symposium held at the Annual Meeting of the Geological Society of America in Denver, Colorado, in October 2002; we thank Cathryn Manduca and David Mogk for organizing the symposium and all the participants for stimulating discussions. We are grateful to Gary Ernst, Cathy Manduca, Dave Mogk, and two anonymous reviewers for their valuable comments on an earlier draft of the manuscript. We thank Maureen Anders, Linda Pistolesi, and Margaret Turrin for their assistance with illustrations. This research was supported by the National Science Foundation under grant no. GEO 01-22001, GEO 03-31212, and REC 04-11823. This is Lamont-Doherty Earth Observatory contribution number 6926.

## REFERENCES CITED

Acredolo, L.P., 1976, Frames of reference used by children for orientation in unfamiliar spaces, *in* Moore, G.T., and Golledge, R.G., eds., Environmental knowing: Theories, research, and methods: Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, p. 165–172.

Acredolo, L.P., 1977, Developmental changes in the ability to coordinate perspectives of a large-scale space: Developmental Psychology, v. 13, p. 1–8, doi: 10.1037//0012-1649.13.1.1.

Allen, J.R.L., 1970, Physical processes of sedimentation: New York, American Elsevier, 248 p.

Anderson, R.N., 1986, Marine geology: A planet Earth perspective: New York, Wiley, 336 p.

Bartlett, F.C., 1932, Remembering: A study in experimental and social psychology: Cambridge, Cambridge University Press, 337 p.

Blatt, H., Middleton, G., and Murray, R., 1972, Origin of sedimentary rocks: Englewood Cliffs, New Jersey, Prentice-Hall, 634 p.

Bryant, K.J., 1982, Personality correlates of sense of direction and geographical orientation: Journal of Personality and Social Psychology, v. 43, p. 1318–1324, doi: 10.1037//0022-3514.43.6.1318.

Carroll, J.B., 1993, Human cognitive abilities: A survey of factor-analytic studies: Cambridge, Cambridge University Press, 829 p.

Carter, C., LaRussa, M., and Bodner, G., 1987, A study of two measures of spatial ability as predictors of success in different levels of general chemistry: Journal of Research in Science Teaching, v. 24, p. 645–657.

Chase, W.G., and Simon, H.A., 1973, Perception in chess: Cognitive Psychology, v. 4, p. 55–81, doi: 10.1016/0010-0285(73)90004-2.

Chi, M.T.H., Feltovich, P.J., and Glaser, R., 1981, Categorization and representation of physics problems by experts and novices: Cognitive Science, v. 5, p. 121–152.

Collins, A.M., and Quillian, M.R., 1969, Retrieval time from semantic memory: Journal of Verbal Learning and Verbal Behavior, v. 8, p. 240–248, doi: 10.1016/S0022-5371(69)80069-1.

Downs, R.M., and Liben, L.S., 1991, The development of expertise in geography: A cognitive-developmental approach to geographic education: Annals of the Association of American Geographers, v. 81, p. 304–327, doi: 10.1111/j.1467-8306.1991.tb01692.x.

Eliot, J., and Smith, I.M., 1983, An international directory of spatial tests: Windsor, UK, NFER-Nelson, 458 p.

Farber, P.L., 2000, Finding order in nature: The naturalist tradition from Linnaeus to E.O. Wilson: Baltimore, Johns Hopkins University Press, 152 p.

Geography Education Standards Project, 1994, Geography for life: National Geography Standards 1994: Washington, D.C., National Geographic Research and Exploration, 272 p.

Gilhooly, K.J., Wood, M., Kinnear, P.R., and Green, C., 1988, Skill in map reading and memory for maps: The Quarterly Journal of Experimental Psychology, v. 40A, p. 87–107.

Glen, W., 1982, The road to Jaramillo: Critical years of the revolution in earth science: Stanford, California, Stanford University Press, 459 p.

Hamblin, W.K., 1994, Introduction to physical geology (2nd edition): New York, Macmillan, 400 p.

Hanawalt, N.G., 1942, The effect of practice upon the perception of simple designs masked by more complex designs: Journal of Experimental Psychology, v. 31, p. 134–148.

Hart, R.A., and Moore, G.T., 1973, The development of spatial cognition: A review, *in* Downs, R.M., and Stea, D., eds., Image and environment: Cognitive mapping and spatial behavior: Chicago, Aldine, p. 246–288.

Hegarty, M., and Sims, V.K., 1994, Individual differences in mental animation during mechanical reasoning: Memory & Cognition, v. 22, p. 411–430.

Hobbs, B.E., Means, W.D., and Williams, P.F., 1976, An outline of structural geology: New York, Wiley, 512 p.

Hock, H.S., Gordon, G.P., and Marcus, N., 1974, Individual differences in the detection of embedded figures: Perception & Psychophysics, v. 15, p. 47–52.

Hurlbut, C.S., Jr., 1971, Dana’s manual of mineralogy (18th edition): New

York, Wiley, 530 p.

Hutton, J., 1788, Theory of the earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the globe: Transactions of the Royal Society of Edinburgh, v. 1, pt. 2, p. 209–304 (available online at http://www.uwmc.uwc.edu/geography/hutton/hutton.htm).

International Commission on Zoological Nomenclature, 1985, International code of zoological nomenclature (3rd edition): Berkeley, University of California Press, 338 p.

Ishikawa, T., and Kastens, K.A., 2005, Why some students have trouble with maps and other spatial representations: Journal of Geoscience Education, v. 53, p. 184–197.

Kail, R., and Park, Y., 1990, Impact of practice on speeded mental rotation: Journal of Experimental Child Psychology, v. 49, p. 227–244, doi: 10.1016/0022-0965(90)90056-E.

Kastens, K.A., and Ishikawa, T., 2004, Why some students have trouble with maps and spatial representations: An on-line tutorial for geoscience faculty: http://www.ldeo.columbia.edu/edu/DLESE/maptutorial. **[[Please provide month and year site was accessed.]]**

Kastens, K.A., Kaplan, D., and Christie-Blick, K., 2001, Development and evaluation of a technology-supported map-skills curriculum, *Where are We?*: Journal of Geoscience Education, v. 49, p. 249–266.

Keller, E.F., 1983, A feeling for the organism: The life and work of Barbara McClintock: New York, Freeman, 272 p.

Kennett, J.P., 1982, Marine geology: Englewood Cliffs, New Jersey, Prentice-Hall, 813 p.

Kyllonen, P.C., Lohman, D.F., and Snow, R.E., 1984, Effects of aptitudes, strategy training, and task facets on spatial task performance: Journal of Educational Psychology, v. 76, p. 130–145, doi: 10.1037//0022-0663.76.1.130.

Lakoff, G., 1987, Women, fire, and dangerous things: What categories reveal about the mind: Chicago, University of Chicago Press, 632 p.

Lakoff, G., and Johnson, M., 2003, Metaphors we live by: Chicago, University of Chicago Press, 2nd edition, 256 p.

Lamont-Doherty Earth Observatory, 2001, Citation for award of first Lamont-Doherty Heritage Award: http://www.earthinstitute.columbia.edu/news/aboutStory/about7_1_01.html (accessed October 2002).

Lawrence, D.M., 1999, Mountains under the sea: Mercator's World, Nov/Dec issue, p. 36–43.

Lawrence, D.M., 2002, Upheaval from the abyss: Ocean floor mapping and the earth science revolution: New Brunswick, New Jersey, Rutgers University Press, 248 p.

Lesgold, A.M., Rubinson, H., Feltovich, P.J., Glaser, R., Klopfer, D., and Wang, Y., 1988, Expertise in a complex skill: Diagnosing X-ray pictures, *in* Chi, M.T.H., Glaser, R., and Farr, M., eds., The nature of expertise: Hillsdale, New Jersey, Erlbaum, p. 311–342.

Levine, M., Jankovic, I.N., and Palij, M., 1982, Principles of spatial problem solving: Journal of Experimental Psychology, General, v. 111, p. 157–175, doi: 10.1037//0096-3445.111.2.157.

Levine, M., Marchon, I., and Hanley, G., 1984, The placement and misplacement of you-are-here maps: Environment and Behavior, v. 16, p. 139–157.

Levinson, S.C., 1996, Frames of reference and Molyneux's question: Cross-linguistic evidence, *in* Bloom, P., Peterson, M.A., Nadel, L., and Garrett, M.F., eds., Language and space: Cambridge, Massachusetts, Massachusetts Institute of Technology (MIT) Press, p. 109–169.

Liben, L.S., 1978, Performance on Piagetian spatial tasks as a function of sex, field dependence, and training: Merrill-Palmer Quarterly, v. 24, p. 97–110.

Liben, L.S., 1991, Adults' performance on horizontality tasks: Conflicting frames of reference: Developmental Psychology, v. 27, p. 285–294, doi: 10.1037/0012-1649.27.2.285.

Liben, L.S., and Downs, R.M., 1993, Understanding person-space-map relations: Cartographic and developmental perspectives: Developmental Psychology, v. 29, p. 739–752, doi: 10.1037/0012-1649.29.4.739.

Liben, L.S., and Golbeck, S.L., 1984, Performance on Piagetian horizontality and verticality tasks: Sex-related differences in knowledge of relevant physical phenomena: Developmental Psychology, v. 20, p. 595–606, doi: 10.1037//0012-1649.20.4.595.

Linn, M.C., and Petersen, A.C., 1985, Emergence and characterization of sex differences in spatial ability: A meta-analysis: Child Development, v. 56, p. 1479–1498.

Marr, D., 1982, Vision: A computational investigation into the human representation and processing of visual information: New York, Freeman, 397 p.

Marshak, S., 2001, Earth: Portrait of a planet: New York, Norton, 735 p.

Mathewson, J.H., 1999, Visual-spatial thinking: An aspect of science overlooked by educators: Science & Education, v. 83, p. 33–54, doi: 10.1002/(SICI)1098-237X(199901)83:1<33::AID-SCE2>3.0.CO;2-Z.

Mayer, R.E., and Sims, V.K., 1994, For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning: Journal of Educational Psychology, v. 86, p. 389–401, doi: 10.1037/0022-0663.86.3.389.

McBurney, D.H., Gaulin, S.J.C., Devineni, T., and Adams, C., 1997, Superior spatial memory of women: Stronger evidence for the gathering hypothesis: Evolution and Human Behavior, v. 18, p. 165–174, doi: 10.1016/S1090-5138(97)00001-9.

McGeary, D., and Plummer, C.C., 1998, Physical geology: Earth revealed (3rd edition): Boston, McGraw-Hill, 592 p.

McGee, M.G., 1979, Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences: Psychological Bulletin, v. 86, p. 889–918, doi: 10.1037//0033-2909.86.5.889.

Merriwether, A.M., and Liben, L.S., 1997, Adults' failures on Euclidean and projective spatial tasks: Implications for characterizing spatial cognition: Journal of Adult Development, v. 4, p. 57–69.

National Research Council, 2006, Learning to think spatially: Washington, D.C., The National Academies Press, 313 p.

Owen, C., Pirie, D., and Draper, G., 2001, Earth lab: Exploring the earth sciences: Pacific Grove, California, Brooks/Cole, 432 p.

Pallrand, G., and Seeber, F., 1984, Spatial ability and achievement in introductory physics: Journal of Research in Science Teaching, v. 21, p. 507–516.

Piaget, J., 1983, Piaget's theory, *in* Kessen, W., ed., Handbook of child psychology. Volume 1: History, theory, and methods (4th edition): New York, Wiley, p. 103–128.

Piaget, J., and Inhelder, B., 1967, The child's conception of space (trans. F.J. Langdon and J.L. Lunzer): New York, Norton (original work published 1948, 512 p.).

Piburn, M., 1980, Spatial reasoning as a correlate of formal thought and science achievement for New Zealand students: Journal of Research in Science Teaching, v. 17, p. 443–448.

Piburn, M., Reynolds, S.J., McAuliffe, C., Leedy, D.E., Birk, J.P., and Johnson, J.K., 2005, The role of visualization in learning from computer-based images. International Journal of Science Education, v. 27, p. 513–527.

Pitman, W.C., III, and Heirtzler, J.R., 1966, Magnetic anomalies over the Pacific-Antarctic Ridge: Science, v. 154, p. 1164–1171.

Ramsay, J.G., and Huber, M.I., 1983, The techniques of modern structural geology. Volume 1: Strain analysis: London, Academic Press, 307 p.

Ramsay, J.G., and Huber, M.I., 1987, The techniques of modern structural geology. Volume 2: Folds and fractures: London, Academic Press, 391 p.

Rochford, K., 1985, Spatial learning disabilities and underachievement among university anatomy students: Medical Education, v. 19, p. 13–26.

Rodgers, J., 1990, Fold-and-thrust belts in sedimentary rocks. Part 1: Typical examples: American Journal of Science, v. 290, p. 321–359.

Rodgers, J., 2001, The company I kept; autobiography of a geologist: Transactions of the Connecticut Academy of Arts and Sciences, v. 58, p. 224.

Rosch, E., 1978, Principles of categorization, *in* Rosch, E., and Lloyd, B.B., eds., Cognition and categorization: Hillsdale, New Jersey, Erlbaum, p. 27–48.

Russell-Gebbett, J., 1984, Pupils' perceptions of three-dimensional structures in biology lessons: Journal of Biological Education, v. 18, p. 220–226.

Sclater, J., and J. Francheteau, 1970, The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the Earth: Geophysical Journal of the Royal Astronomical Society, v. 20, p. 493–509.

Sclater, J.G., Anderson, R.N., and Bell, M.L., 1971, Elevation of ridges and evolution of the central eastern Pacific: Journal of Geophysical Research, v. 76, p. 7888–7915.

Shepard, R.N., and Feng, C., 1972, A chronometric study of mental paper folding: Cognitive Psychology, v. 3, p. 228–243, doi: 10.1016/0010-0285(72)90005-9.

Shepard, R.N., and Metzler, J., 1971, Mental rotation of three-dimensional objects: Science, v. 171, p. 701–703.

Siegel, A.W., and White, S.H., 1975, The development of spatial representations of large-scale environments, *in* Reese, H.W., ed., Advances in child development and behavior, vol. 10: New York, Academic Press, p. 9–55.

Silverman, I., and Eals, M., 1992, Sex differences in spatial abilities: Evolutionary theory and data, *in* Barkow, J.H., Cosmides, L., and Tooby, J., eds., The adapted mind: Evolutionary psychology and the generation of culture: New York, Oxford University Press, p. 533–549.

Simpson, G.G., 1940, Types in modern taxonomy: American Journal of Science, v. 238, p. 413–431.

Thomas, H., and Jamison, W., 1975, On the acquisition of understanding that still water is horizontal: Merrill-Palmer Quarterly, v. 21, p. 31–44.

Thomas, H., Jamison, W., and Hummel, D.D., 1973, Observation is insufficient for discovering that the surface of still water is invariably horizontal: Science, v. 181, p. 173–174.

Thorndyke, P.W., and Hayes-Roth, B., 1982, Differences in spatial knowledge acquired from maps and navigation: Cognitive Psychology, v. 14, p. 560–589, doi: 10.1016/0010-0285(82)90019-6.

Tooby, J., and Cosmides, L., 1992, The psychological foundations of culture, *in* Barkow, J.H., Cosmides, L., and Tooby, J., eds., The adapted mind: Evolutionary psychology and the generation of culture: New York, Oxford University Press, p. 19–136.

Tuckey, H., and Selvaratnam, M., 1993, Studies involving three-dimensional visualization skills in chemistry: A review: Studies in Science Education, v. 21, p. 99–121.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level, *in* Payton, C.E., ed., Seismic stratigraphy: Applications to hydrocarbon exploration: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 49–212.

Vandenberg, S.G., and Kuse, A.R., 1978, Mental rotations, a group test of three-dimensional spatial visualization: Perceptual and Motor Skills, v. 47, p. 599–604.

Vasta, R., Knott, J.A., and Gaze, C.E., 1996, Can spatial training erase the gender differences on the water-level task?: Psychology of Women Quarterly, v. 20, p. 549–567.

Voyer, D., Voyer, S., and Bryden, M.P., 1995, Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables: Psychological Bulletin, v. 117, p. 250–270, doi: 10.1037/0033-2909.117.2.250.

Warren, D.H., and Scott, T.E., 1993, Map alignment in traveling multisegment routes: Environment and Behavior, v. 25, p. 643–666.

Wegener, A.L., 1929, The origin of continents and oceans (3rd edition) (trans. J. Biram 1966): New York, Dover, 246 p.

Winchester, S., 2001, The map that changed the world: William Smith and the birth of modern geology: New York, HarperCollins, 352 p.

MANUSCRIPT ACCEPTED BY THE SOCIETY 21 MARCH 2006

Printed in the USA