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Journal of College Science Teaching
Vol. 33 No. 1, p. 26-31
September/October 2003
Feature

Alphatome--Enhancing Spatial Reasoning

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Using refrigerator magnets, foam blocks, ink pads, and modeling clay, students manipulate the letters of the alphabet at multiple angles, reconstructing three-dimensional forms from two-dimensional data. This exercise increases students' spatial reasoning ability, an important component in many scientific disciplines.

“Thought can only replace action on the basis of the data which action itself provides” (Piaget and Inhelder 1960, 453).

Three-dimensional (3D) models effectively convey the spatial complexity of natural forms. Students also see representations of nature that are 2D, whether on the printed page, computer monitor, or microscope slide. A special lesson in life’s geometry occurs when the same object is presented in both 2D and 3D views as multiple crosscutting planes through a solid. In biology classes, for example, students may view dozens of thin sections under the microscope to reconstruct a plant organ or a tiny animal embryo. On a larger scale, geologists use natural slices through the landscape to map formations and folds that would otherwise be hidden. Architects and engineers do the same for fabricated structures when they dissect 3D buildings and bridges into 2D maps from every angle.

In these domains it is the *correspondence* between the 2D and 3D views that is most important for communication and learning in the discipline. For example, without comparing each slice to the general structure of the body, a physician could not interpret correctly the hundreds of slices from a magnetic resonance image (MRI) or computed tomography (CAT) scan. One source of information without the other is incomplete. Yet this aspect of spatial thinking in science is often unappreciated, and even if understood is difficult to isolate and teach.

Spatial reasoning has been an important component of pedagogical research for decades. The mid– twentieth century child psychologist Jean Piaget declared that “if the development of various aspects of child thought can tell us anything about the mechanism of intelligence and the nature of human cognition in general, the problem of space must surely rank as of the highest importance” (Piaget and Inhelder 1960, vii). Since that time, educators have debated whether “visual thinking” is separate from other modes of cognition, whether the ability to mentally manipulate shapes is innate or can be instructed (Lord 1985 and 1990), and whether increased spatial aptitude improves performance in science, as well as other subjects.

Interestingly, the mental milestones of spatial reasoning that involve 2D sections or projections seem to arrive late in development, well into the teenage years. Specifically, Russell-Gebbett (1984 and 1985) found that only between the ages of 11 and 15 could most students predict the appearance of a geometric plane intersecting a simple cone or sphere. Many students at these ages could not reconstruct a simple solid when presented with a set of crosscutting plane figures. It is thus unlikely that the average undergraduate can automatically make the proper connections between 3D and 2D information, especially if the learning domain is new.

What is certain about spatial reasoning in science is that very few college labs directly address it. According to a recent review, even veterinary students in advanced animal dissection courses “do not get instruction *specifically* designed to promote spatial reasoning, nor are they tested for mastery in this domain” (Provo, Lamar, and Newby 2002, 11).

To address this, I have developed a short exercise to enhance students’ spatial reasoning when considering 2D slices through a 3D form. I call it “Alphatome.” Although its name derives from the histological microtome—a machine that cuts very thin slices from a larger block of tissue—the exercise is applicable to any discipline because the objects sliced are the letters of the alphabet.

Letters are used because students already have the basic shapes memorized; no learning is required. Yet, when presented at unfamiliar angles, letters are spatially complex and even challenging. Most importantly, using these identifiable objects allows students to master spatial reasoning *per se* before confronting any scientific content. This is especially useful in nonmajors science classes, where discipline-specific vocabulary and lab skills may be lacking. The exercise is also valuable in upper-level classes for refreshing spatial skills before advanced studies.

Welcome to Flatland

In my own discipline (embryology) microscopic specimens are often presented as 2D slices laboriously cut from paraffin or plastic blocks on a rotary microtome. Each section, a few microns thin, is stained and mounted on a glass slide, alone or in series. Such slides are used extensively in anatomy, histology, and botany courses and form the core of many biology teaching collections.

In 1999, I taught my first embryology course and incorporated many such slides. Students were required to draw and label dozens each week. In the same labs, students dissected examples of whole animal embryos and also accessed interactive digital views where 2D and 3D information could be swiftly cross-correlated. My idea of integrating all these spatial perspectives was to show as many 2D and 3D images as possible, leaving students to make their way among them while I pointed out key features or landmarks.

I began to scrutinize what students retained from this approach after altering lab requirements the following year. Instead of requiring weekly lab reports, I had students keep a lab notebook and meet with me several times per quarter to discuss their work. Most students could easily comprehend the whole embryos, which were drawn and perceived as miniature animals. Most, if not all, students were quite good at drawing the contours of the flat sections they observed, and they accurately labeled structures in the sections that were comparable to the textbook or lab guide. But, although I saw each section as an arbitrary 2D subset of a 3D embryo, students generally perceived 2D images—whether on slides or on the computer—as just flat. Most were not able to locate their plane of section on a model of the 3D original. Nor could they draw an alternative 2D result if I asked them to show how their embryo would look if it had been cut in another plane.

Students' inability to understand the correspondence between 2D and 3D representations of the same entity repeats the central quandary of the novel *Flatland* (Abbott 1899). In this book, a Square takes a miraculous journey into the third dimension, guided by a kindly Sphere. Before the trip, the Square has no knowledge of higher dimensionality and no language to describe where such a dimension might be.

Students are in a similar position, but with the destinations reversed. As lifelong inhabitants of Spaceland, they have not been made to think in flat planes, or to consider how a complex object might present itself two-dimensionally. And in my busy lab period I left barely enough time to see all the specimens, let alone have students make mental connections among the different dimensional views.

I wondered if I could supplement students' spatial skills without using challenging biology jargon and making them endlessly click through digital views. I soon devised a rapid, inexpensive sectioning simulation that challenged students to assemble both 2D and 3D views of familiar forms before attempting to examine complex embryos. For my specimens I chose the letters of the alphabet, in several guises, as described below.

The Lab in Four Parts

The lab has four parts, which take about 90 minutes altogether. Each segment is of increasing difficulty, and each can stand alone. A general outline of the parts and a list of supplies is given in Figure 1. The handout I give embryology students is available for download atwww.depaul.edu/~biology/leclair/alphatome.htm.

FIGURE 1

Alphatome exercise outline.

Parts and goals	Supplies needed
1.The set-up: Introduce letters as 3D specimens.	Magnet letters (A to Z), magnetic board.
2.The problem: Cut up foam blocks and make "letter prints." Demonstrate the loss of information after 2D slicing.	Foam blocks in the shape of letters, finger paint or ink pads, colored construction paper, and scissors.
3.The block: Make a block with a modeling clay letter enclosed. Slice, draw, and reconstruct the known letter from serial sections.	Two contrasting colors of modeling clay (approximately one can of each color per team), 4"x 6" card, thin plastic ruler, white drawing paper, and colored pencils.
4.The challenge: Make a challenge block for another team. Slice, draw, and reconstruct the unknown letter from serial sections.	Same as for part 3.

The set-up: (5 min). I begin by pushing magnet letters around the surface of the nearest whiteboard (Figure 2). The magnets should have depth as well as width and height; this third dimension is critical for starting students thinking spatially. I explain that these will be our lab "specimens" and that each has a unique shape. The shape remains constant, no matter how the letter is oriented.

The problem (10 to 15 min). Letter identification gets more challenging when the familiar angle of presentation is removed. I illustrate this by passing some of the magnets around the classroom for students to handle. I pose the question: What if you were presented with a letter shape from *any* angle? And what if only *two* dimensions, not three, were provided?

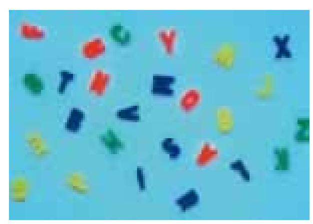

Figure 2. Magnet letters on the whiteboard.

Figure 3. Foam letters.

I demonstrate this problem by producing a set of 3D foam letters and a pair of scissors. (Foam block letters are available at most toy stores or art supply centers and are used in stenciling posters and signs.) Cutting a chosen letter at some angle, I apply paint to the cut surface and print it onto a whiteboard or paper. Making the print on a lighted overhead transparency can also show the effect. The result bears no resemblance to a letter; it is reduced to one or more blobs (Figure 3).

Next, students actively confirm this spatial transformation. Each person gets one or two foam letters and a pair of scissors. Each letter should be cut once on a straight line in some arbitrary direction. After cutting their letter, each student paints the cut face of it and prints its impression on colored paper. Again, the printed mark looks nothing like the letter. Each student then exchanges a completed print with a peer. The receiving student is asked to identify the letter based *only* on the print. Using the process of elimination, students may rule out some of the 26 letters, but rarely is positive identification possible. By this point, students appreciate that this is harder than it seems.

I ask students to reflect on their troubles and to propose how the 2D/3D task of letter identification could be improved. Suggested solutions often include cutting the letter multiple times (to obtain more planes of information) or standardizing the cutting angle (to eliminate variation). We then discuss several points:

- A single crosscutting plane is rarely sufficient to give much information about the letter's identity or orientation. When we want to figure out complex 3D forms, we should simultaneously appreciate information from multiple adjacent 2D slices. This means serial sections, which we attempt next.
- The choice of plane through any object is both infinite and arbitrary. Just as no two students will cut the same letter at the same location, there is nothing to prevent us from slicing a specimen in any way whatsoever. Even if we attempted to standardize the cutting plane for convenience, human error and imperfections would prevent making perfect replicas. This is why actual slices through cells, tissues, polymers, sediments, or any other structures do not always match 2D textbook illustrations and can look radically different, even when the angle is only slightly changed.

The block (30 min). The next task is to build a 3D letter, then slice it serially into 2D sections. Individually or in small groups, students pick two contrasting modeling clay colors. One color will be the letter material, and one will be the background material. Students then select one letter as a model. For variety, I try to spread their choices among three groups, based on the capital letter's typical structure:

- *Straight and Pointy:*
  A, E, F, H, I, K, L, M, N, T, V, W, X, Y, Z
- *Round and Curvy:*
  C, G, O, Q, S
- *Straight and Curvy:*
  B, D, J, P, R, U

Students roll the letter color of modeling clay into small, uniform logs about 1 cm in diameter and use them to form two identical sculptures of the chosen letter. To be standard in size, each letter should be as large as, but no larger than, the outline of a 4" x 6" card. No gaps or breaks should appear where the modeling clay pieces are joined or they will show up in the steps that follow.

Next, students fashion two rectangular bases of the background color, about 1-cm thick and just a little bit larger than the letter sculptures. They put one letter sculpture on top of each base and gently press down; mold or cut more background color to completely fill up all the gaps around the letters, creating a level upper surface; shape two more rectangular bits of background material the same size as the bases; and gently put these on top, press down, and then seal the edges to get two completed letter blocks (Figure 4A). At this stage, one can mark each block to remember which end is "up" or deliberately obscure the orientation of the letter.



Figure 4a. A completed letter block. **Figure 4b.** Cutting downward. **Figure 4c.** A typical set of slices.

I organize the cutting exercise with several rules. One student in each pair takes one of the two blocks they have constructed. Each student must cut his or her block in a *different* orientation. Athough there are infinite angles to choose from, we stick to the easy choices such as parallel to the base of the letter, or parallel to the height of the letter. Most other angles add considerable challenge, even at this stage when the letter is known. Students cut one slice at a time in a serial fashion. A thin, flexible plastic ruler is used to cut downward with a gentle rocking motion (Figure 4B); rapid slicing causes serious compression and “ripping out.” A typical block yields eight to 10 slices, each about 1-cm thick (Figure 4C).

Each block thus yields a slightly different set of slices representing the same letter form. The endpoint of this phase is when students can conclude that the same 3D form was indeed the starting point for the two sets of 2D data, *using the slices as evidence and spatial reasoning as an argument*. Students must justify their conclusion using observation, drawing, and mental assembly of the slices, not their prior knowledge of the starting 3D form.

To reinforce this thinking, I require a full set of 2D drawings to be installed in the lab notebooks (Figure 5), along with a written narrative. The narrative tells an outside observer what the letter is and how its 3D identity can be deduced solely from the two different but equivalent 2D representations.

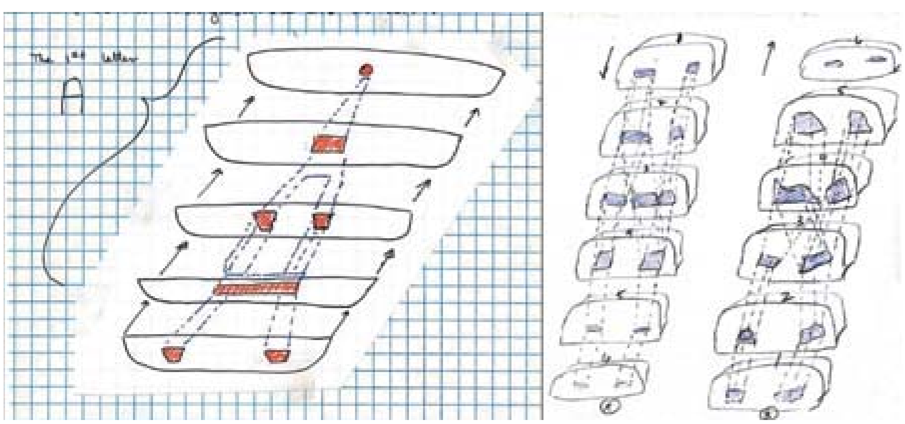

Figure 5. Student drawings of the challenge exercise. Left: A reconstruction of the letter "A." Right: The letters "N" and "X."

The challenge (30 min). In the final phase, students repeat the previous exercise with an unknown letter to reinforce the spatial reasoning task. Each group makes one “challenge block” containing a single letter in any orientation, which they exchange with another team. The blocks are numbered for reference, but the enclosed object is a mystery. Because the receiving team does not know the 3D form, the only identification can come from analyzing slices as practiced earlier.

Students must draw each slice, interpret what they see, and support their conjectures about the 3D form using only the patterns in front of them. If time permits, I call on one team to draw their evidence on the board and present their reasoning verbally. In the final notebook, each person is required to present a set of drawings and write a convincing argument about the letter's identity using their modeling clay data as support.

Finally, as in real science, the simulation mimics the artifacts and uncertainties of acquiring and assembling multiple 2D instances of an irreplaceable 3D specimen. Rarely are the data clean or perfect. Student letters will contain flaws of manufacture. The slicing process will add significant compression and distortion. Mishaps can mangle a crucial section or crash the entire specimen—a valuable lab lesson. Students may find that accurate analysis is not possible and that the best answer is uncertainty about the letter's identity.

Student Response

Although simple, the Alphatome exercise has contributed significantly to student learning in my upper-level embryology course where 2D representations are important tools. It remains one of the more popular labs, perhaps because of its novelty and contrast to traditional "wet" labs. In 2002, 18 junior and senior biology majors and three biology master's students participated. Each student wrote a short reaction paper to the lab, describing what they learned and offering criticism. Of the 21 responses received, 18 were positive. Many commented on the novelty and challenge of the exercise as a test of general spatial reasoning:

- I was surprised to realize the difficulty of forming the 3D figure and connecting all the slices together, even knowing what the starting whole model was.
- Even though I am very familiar with the letters, it was fairly difficult to discern which one was the mystery one. The only way I was able to discover [it] was by piecing everything together. In real cross sections this will probably be very important.

Others described how this new-found spatial reasoning could be applied specifically to their biology curriculum:

- Before the lab I thought this was going to be a useless lab of just playing with modeling clay, but it turned out to be *very* informative and *very* beneficial. The exercise fulfilled its purpose of helping us conceptualize sections.
- I have always known what the 3D organism looks like and what the microscope slide looks like and have never made much of a correlation between the two. This exercise really demonstrated how difficult the process of recreating and visualizing the 3D object from the 2D [slice] really is.
- I could have used this lab when I was an undergraduate in histology. I may bring this idea to histology class to help them understand why everything does not look the way it does in the book, the perfect picture.
- I found it funny that I have been viewing slides throughout my career as a student and never was really able to reconstruct the image I was viewing in a larger way.

Three of the 21 responses were neutral or negative toward the exercise. These students felt that it was too basic or not relevant to their needs. Specifically criticized were the simple materials and methods ("This was way too kindergarten"), the apparent lack of science content ("Why are we doing this art stuff in bio class?"), and the absence of easily absorbed, memorable facts ("I don't see how this is going to help me on the MCAT!").

Teachers who adopt this lab might want to confront these student perceptions in advance, during the introduction. I now repeatedly emphasize the contrast between verbal and spatial reasoning and the importance of both in the sciences. In addition, more 2D and 3D views are now incorporated into the course's lab write-ups and exams, increasing the "payoff' of the activity.

Alphatome is a fun, fast, and inexpensive way to stimulate spatial reasoning for science students in any discipline. In my embryology course, students participating in the exercise felt better prepared to view microscope slides, newly appreciating a common lab prop they had seen many times before. Similar skills might benefit students of chemistry, geology, environmental science, engineering, or any class in which 2D and 3D views of an object are compared. Indeed, these skills are probably necessary at much earlier levels of education but are rarely taught by themselves.

The idea of modeling cross- cutting sections through a larger, more complex form is not new. Foote suggested using clay of different colors to sculpt the body wall of a fish (1981). Students would then cut the sculpture along different planes. These sections would match 2D figures in the textbook, allowing students to actively learn the difference between sagittal, transverse, and cross sections through the organism. This kind of spatial reasoning is not required by the life sciences alone. Similar exercises have been devised for geology classrooms using cuts through wooden blocks (Shettel and Curley 1995) and layer cakes (Wagner 1987).

The Alphatome strategy, although similar in physical principle, differs in using letters as study objects. Thus, no discipline-specific background is required, and the pedagogical objective of enhancing spatial skills is not confounded with other learning goals. This allows it to be applied to any course and to aid students who have little or no experience in the core subject, particularly nonmajors.

The lab's four parts start simply and build rapidly to a complex level. This steep learning curve creates an immediate sense of progress and personal mastery in the spatial reasoning realm. In contrast, the skills to interpret "professional" 2D/3D representations might only come with months or years of training. This is a formula with little appeal for a beginning student in a quarter or semester course. Finally, the lab repeats the action of slicing and interpreting crosscutting planes at least three times, using slightly different objects (paper, foam, and clay). This creates a learning cycle where spatial reasoning is rehearsed and positively reinforced.

Just as for the Squares in *Flatland*, the transition between two and three dimensions can seem miraculous. Words often fail when we try to convey its mysteries, which cannot be memorized. Yet knowing how important the skill is, I have found it worthwhile to allow students a hands-on entrance to both worlds.

Having mastered dimensional transformations in the arena of letters, foam, paper, and modeling clay, students are better prepared to confront similar problems in other domains.

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Acknowledgments

A version of this report was presented at the 2002 Educational Symposium of the Society for Developmental Biology, Madison, Wisconsin. I thank R. Edwards and T. Sparkes (DePaul University) for helpful comments on the manuscript.

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