34. Elisabeth Butler, "The Developmental Capacity of Regions of the Unincubated Chick Blastoderm as Tested in Chorio-Allantoic Grafts," *Journal of Experimental Zoology* 70 (1937): 287–338; Mary E. Rawles, "The Pigment-Forming Potency of Early Chick Blastoderm," *Proceedings of the* U.S. National Academy of Sciences 26 (1940): 91.

35. Cf. Wetzel's figure 120 (Wetzel, "Untersuchungen am Hühnchen," 311) and compare to Rawles's figures 7–9 (Rawles, "A Study in the Localization of Organ-Forming Area," 308–9).

36. Emil Witschi, *Development of Vertebrates* (Philadelphia: Saunders, 1956), fig. 137b, 247.

37. Rudnick, "Early History," 206.

38. Ibid., 205.

39. Dorothy Rudnick, "Prospective Areas and Differentiation Potencies in the Chick Blastoderm," *Annals of the New York Academy of Sciences* 49, no. 5 (1948): 763–64.

40. Rudnick, "Prospective Areas," 771–72.

41. Karl Ernst von Baer, *Entwickelungsgeschichte der Thiere*, vol. 1 (Königsberg: Borntraeger, 1828), xix. For Baer's reflection on dimensionality and the difficulty of how to visualize a developing embryo on flat paper, see Sabine Brauckmann "Axes, Planes and Tubes, or the Geometry of Embryogenesis," *Studies in History and Philosophy of Biological and Biomedical Sciences* (forthcoming, 2011).

42. William M. Ivins, *Prints and Visual Communications* (Cambridge, MA: Harvard University Press, 1953).

chapter ten

# Form and Function

## A Semiotic Analysis of Figures in Biology Textbooks

Laura Perini

The explosive growth of the life sciences in the twentieth century poses significant pedagogical challenges for college-level education in biology. Life science majors must learn basic concepts from domains as diverse as biochemistry and biogeography. Majors are usually required to take one or more introductory-level courses that each covers a very broad domain, as preparation for more advanced courses, which focus on subfields or topics. Genuine understanding requires more than simply learning disparate concepts: students must grasp key connections among different topics, such as those between the structure of DNA and the theory of natural selection. The introductory courses thus play an important role in educating life science majors. Students must understand the overall landscape of biology in such a way that they are prepared both to study a variety of individual topics in depth, and to maintain (and ideally, strengthen) their grasp on how those different topics relate to one another. How, precisely, is all of this accomplished? How do students learn such diverse content? How do they achieve genuine understanding—in particular of the linkages between different topics they encounter in their introductory biology classes?

Textbooks are important educational tools in such courses. They are repositories of the bulk of the information presented. Their use outside of classroom settings gives individual students much greater control over the pace and sequence of information delivery. On the other hand, their content is static, in contrast to live instruction, which can be adjusted at any time to clarify, explain, and elaborate as needed in response to questions or blank stares. Textbooks also do not offer the social interactions and experiential feedback available in laboratory work. Unread books offer no advantages at all: in order to complement classroom instruction, textbooks must be engaging as well as comprehensible. As learning tools, both their greatest advantages and most serious liabilities stem from the fact that textbooks are individual student-managed resources.

These are the general advantages and constraints of textbooks. As noted, biology has undergone a dramatic increase in explanatory depth and breadth in the twentieth century. This growth in the discipline is matched by changes in college-level biology textbooks, indicating that textbooks are being used as one means of meeting the specific pedagogical challenges involved in teaching contemporary biology. Woodruff's 1926 publication, *Foundations of Biology*, has 411 pages in the body of the text.[1] Contemporary introductory textbooks are much larger: they are typically in the neighborhood of 1,100 pages long. But comparison in page numbers can give only a rough idea of the degree to which biology textbooks have changed, because the number of figures presented has increased far more than the number of pages. Woodruff contains 211 pictures—about one every other page. A midcentury text by G. G. Simpson et al. has many text-only pages.[2] Current editions of general biology textbooks designed for life science majors, on the other hand, are filled with images: a page without a figure is rare, and pages with multiple images are common.[3] The dramatic increase in the relative amount of pictorial content suggests that images are being used in response to the need to present information in a way that addresses the goals of an introductory course—which require students to comprehend and integrate many diverse concepts.

Could images serve such pedagogical goals in the life sciences? Do images really contribute to the cognitive goals of a biology course—or does their value stem only from their aesthetic appeal, serving to attract and hold student attention rather than convey essential content? To address this question, I will investigate three textbooks, which are all designed for introductory courses for life science majors, and together comprise the majority of the market share of college-level major's textbooks.[4] A quick look at a contemporary general textbook may arouse some suspicion, because some of the images do function primarily to draw student interest. Examples include pictures of famous scientists and (often beautiful) photographs of whole organisms when their visual appearance is irrelevant to the point under discussion. But the fact that *some* figures play such a limited role does not imply that all do. Can figures make a substantive pedagogical contribution? If so, just what do they have to offer? Are they an effective learning tool for particular concepts? Can they do even more—can they help students understand connections among different concepts?



These questions cannot be given general answers, because there is significant variety *among* the figures in biology textbooks. The growing literature on scientific images presents reasons to doubt that some figures—detailed pictures, like photographs or electron micrographs—can play such roles effectively. On the other hand, diagrammatic representations have been shown to convey theoretical content that is clearly cognitively significant, and so may have pedagogical value as well.[5] In this paper I will present an analysis of these different kinds of figures in order to clarify their potential pedagogical value. I will show that in spite of the genuine obstacles that have been identified with detailed pictures, they can indeed make important pedagogical contributions. This opens up the question of why both highly detailed as well as visually abstract images are presented in textbooks, but further analysis of diagrams provides an answer: different kinds of diagrams provide different sorts of pedagogical advantages.

## Visual Representation

Textbook figures include drawings, diagrams, and images produced by various kinds of detection processes, like photography and electron microscopy. There are significant differences in the way these images look, how they are made, and the kinds of content they convey. In order to assess their pedagogical contributions, we need to understand what they have in common as visual representations, and how they differ.

In his analysis of images in a biology textbook, Myers approaches this diversity by applying Peirce's tripartite division of signs.[6] Indexical signs have a direct link to the thing referred to, so the form of the image is caused by features of the referent. Iconic signs have forms, which resemble their referents. Symbolic signs refer in virtue of convention; there is an arbitrary relation between their form and their content. While these factors all come into play in scientific visual representations, they cannot be used to sort images into distinct classes, because all visual representations involve both convention and resemblance.[7] Myers himself stresses the blurring of the categories, explaining that his usual motive for applying them is to "make readers more critical of the indexical and iconic end of the scale" by calling into question assumptions about the naturalness of such images;[8] in this paper, Myers's main concern is with highly conventional images and the pedagogical challenges they involve.

Here I offer an alternative semiotics as a means for analyzing the roles of images in biology textbooks. The problem with Peirce's conceptual apparatus is not that the categories are vague, but that they are too general to clarify important similarities and differences among images. It is not the distinction between whether or not an image is conventional or resembles its referent that explains the use of different kinds of images, but the different *kinds* of conventions and resemblance relations involved. Those are significant factors, because they jointly determine the relationship between the form of an image and its content. Differences in form-content relations provide the means to categorize images.[9] Furthermore, they ground explanations for why different kinds of images are suited for different kinds of communicative tasks. For this reason, I'll present my analysis in terms of a semiotic approach that is designed to clarify the relation between form and content.

All visual representations have one thing in common: they use spatial properties of the picture to convey information.[10] This can be done in a variety of ways; protein diagrams use two-dimensional spatial properties of the diagram to represent three-dimensional spatial features of proteins. Graphs use spatial relations to represent relations among properties. Other visible properties may also be used to convey information. For example, color photos use their spatial layout and the colors of the image to represent visible properties of the scene depicted. The use of spatial relations to convey content is, however, the defining feature of visual representations.

Comprehension of any visual representation requires interpretation on the part of the viewer: only by understanding the relation between the form of the image and its content can a person comprehend the image. This understanding is often tacit. We comprehend familiar kinds of pictures so readily that we are rarely aware that it is a cognitive achievement to understand a flat, marked surface as a representation of anything. Our ability to understand various kinds of pictures demonstrates that we can work with many different kinds of form-content relationships: we look at, and/or focus on, different visible features of the image and relate those features to different kinds of properties. Comprehending a black and white photograph requires relating the visible properties of the photo to visible properties of visible objects. But not all visible features of the photo convey information: the fact that brightness ranges on a white-to-black scale rather than through light-to-dark sepia tones is not relevant. Additionally, the visible properties of the image that are interpreted convey information about some, but not all, properties of the referent; specifically, the tones in the photograph are not understood as representing colors of depicted objects. Understanding a color photo depends on interpreting the image according



to a different relation between form and content from that appropriate for black and white photographs. Comprehending a color photograph involves relating a different set of visible properties—now including the specific colors in the photo—to a different set of properties of depicted objects, including their colors. These differences in the form-content relations relevant to different kinds of images underwrite differences in representational capacity. Black and white photos can represent visible properties like relative brightness and spatial features; color photographs convey information about those features and color as well. In both cases, the visible form of the image is related to its content, due to the defining feature of visual representations—the fact that some spatial features are interpreted to represent some feature of the referent. Summing up, interpretation plays an essential role in determining the meaning of every picture, and the kind of interpretation involved varies considerably because the relations between visible form and content vary.

Because all visual representations involve a relation between form and content, they all (in a broad sense) resemble their referents, but those resemblance relations vary; they are not limited to relations of visual resemblance. The conventional aspect of visual representations—the fact that communication with visual representations depends on application of shared interpretive practices, and not just on the visible features of the image—grounds the fact that different visible features in images can be used to represent different kinds of properties. This in turn explains the broad expressive capacity of images, which can be used to represent many different kinds of things. Scientists have exploited this capacity: scientific images are frequently used to represent phenomena that are not visible at all. In such cases, the visible features of the image are interpreted as conveying information about *nonvisible* features of the referent. Some images represent phenomena that are simply too small to be seen, like the helical structure of DNA. Other images represent phenomena that are not even spatial, such as diagrams of mechanisms or graphs of relations between properties. For understanding the value of a particular image, clarifying the relationship between its form and its content sets the stage for articulating what makes the content conveyed by that type of image distinctive, and for explaining why the mode of representation matters.

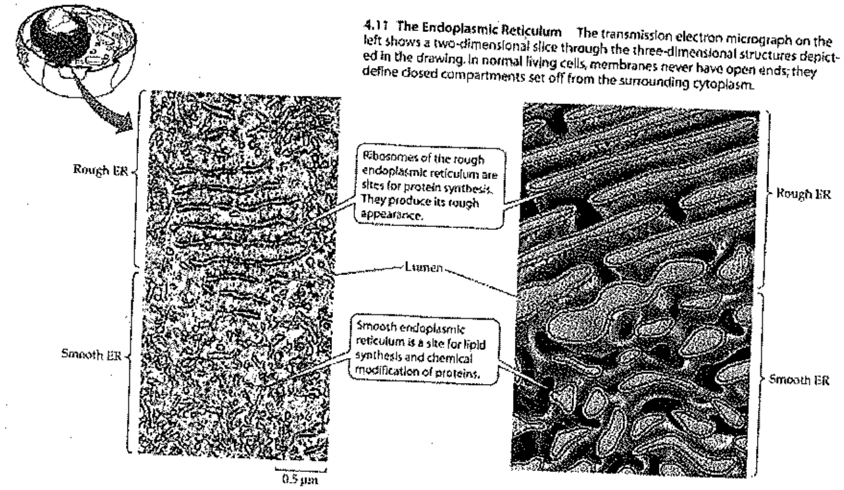
## Replete Pictorial Representations

Some visual representations stand out due to their detailed appearance. Such figures include "naturalistic" drawings or paintings, as well as photographs and other images produced through detection mechanisms, like electron microscopy. Despite the differences within this class of figures, their form-content relationships are all similar in one significant way: Most visible details of the picture are interpreted as conveying information about specific properties of the depicted scene or subject matter. I'll refer to this broad type of visual representation as "pictorial," since it includes familiar types of pictures such as photographs, drawings, and paintings done in naturalistic style. The examples just mentioned involve a form-content relation that correlates specific visible details in the image with specific detailed properties; a particular contour line used to represent a particular shape, for example, or a particular hue used to represent a particular color in the scene. There are two different ways in which detail is important in these images. First, *specific* visible features of the picture convey information about specific properties of the referent. This is the feature that all pictorial representations have in common. Second, *most* of the visible features of the image are interpreted in this way—specific visible features are used to represent specific properties. The fact that most visible features convey meaning in this way is a distinct feature, that of relative repleteness.[11] Visual representations with such a form-content relationship convey large amounts of very specific information.

The use of richly detailed visible forms to convey correspondingly detailed information is common in introductory biology. Textbooks frequently include photographs of medium-sized objects like plants and animals, and photographs made with light microscopes. The form-content relation that defines pictorial representations is also produced by imaging techniques that detect nonvisible features. For example, electron micrographs represent the form of the biological material in a particular specimen through the array of light and dark tones in the figure (figure 10.1, left panel). Images made as a result of mechanisms like electron microscopy are often presented as evidence in research publications. The pictorial nature of the visual representation offers a concise yet comprehensible way to convey information about very complex properties. Also, the visible form of the figure is produced by a mechanism designed to correlate the form of the image with properties of the sample.[12]

How do such images contribute to *learning* biology? These images have






10.1 Electron micrograph (left panel) paired with a schematic diagram (right panel), with text bubbles and pointers, and linked to a schematic diagram of a cell interior (upper left) with an arrow. From *Life: The Science of Biology*, 7th edition, edited by Purves et al. Reproduced with permission from Sinauer Associations and Visuals Unlimited. Photographs copyright D. Fawcett/Visuals Unlimited.

a capacity for detailed representations of biological forms. While this might seem like a representational asset, the literature on scientific images has clarified two issues that present reasons to question their pedagogical usefulness.

First, the large amount of detailed information conveyed about the subject can impede learning, which usually depends on awareness of a particular part of an image, such as the facial expression on a particular chimp in a photograph that depicts that individual amid a group of conspecifics, in a natural setting: Myers identifies this as the problem of "gratuitous detail."[13] Replete pictorial representations fall into this category; photographs, for example, are very visually complex images. If learning requires understanding *which* visible features are significant in terms of the subject at hand, how do students identify those features out of all the detail a photograph presents? Law and Lynch analyze the use of different kinds of images in guidebooks for birdwatchers and find books with more replete images (photographs) less useful for species identification, which requires focusing on a few visible traits that matter for determining which of two similar species has been sighted.[14] The "extra" information about the bird's appearance presented by the more detailed pictorial representations was not helpful because the photos give the reader no guidance about which features, among all those depicted, matter for determining species membership. Less replete images, which have less information about how the birds look but which put the visual emphasis on a few traits that matter for identification, were more helpful in allowing birdwatchers to categorize the birds they saw. Lynch describes the problem with photographs as one of "too much reality," which can cause trouble even for researchers—experts—and thus reinforces the worries about using such images in pedagogical contexts.[15]

A second problem regarding pictorial representations is raised by Daston and Galison's research on the history of objectivity.[16] They look at atlas images, which are intended to provide information about classes of objects. They discuss changes in images over time, focusing on how the human skeleton was depicted. Their examples show that there was little change in terms of the drawing techniques; the skeletons are depicted in naturalistic style. These are pictorial representations: visible detail in the image is used to represent detailed features of the depicted individual. The visible differences among these pictures are due to different choices of *which* skeleton to depict, rather than to differences in *how* to depict a particular skeleton. The use of a type of representation in which visual details convey information about specific properties poses a problem for representing classes whose individual members vary in terms of those specific properties. The atlas authors must choose *which* individual should be depicted in order to best represent the class of individuals. Daston and Galison demonstrate that different atlas makers have embraced different views about which individual is the appropriate representative for the class, such as a typical individual, one with averaged properties, or an ideal.[17] Photographs, like the atlas engravings, are also relatively replete pictorial images: They depict individuals with a particular set of specific properties. The pedagogical value of a photograph requires that students do more than simply comprehend the picture; students must also grasp the relation between the information about that individual and a wider biological category, which includes cases that are similar to that depicted by the photograph, but not identical. The problem of using naturalistic images to represent a biological class is caused by the use of images that represent detailed visible features of referents. While the atlas authors aimed to resolve the problem of instructing about a class by choosing the right individual to depict in detail, contemporary biology textbooks use alternative tactics.

The pedagogical drawbacks of pictorial representations can be mitigated. The problem generated by using a pictorial representation of an individual to represent a class, for example, is often resolved by pairing the pictorial representation with a different kind of visual representation. Since the resolution depends on the distinctive form-content relations of a particular type of diagram, I'll present my support for this claim in the discussion of schematic images.



There are also ways to get around the problem of gratuitous detail. Myers notes that it can be resolved textually. Figure legends are often used to direct attention to significant features, such as a reference to a "play face" expression in the caption of a picture of a group of chimpanzees.[18] Bastide shows how grouping images in clusters can help a reader focus on a significant detail in one that differs from the others.[19] As figure 10.1 shows, the use of lines and arrows superimposed on the image also directs attention to a particular part of an image, and placement of a textual label at the other end of the line indicates a relation between that part of the picture and a linguistically expressed concept.

The pedagogical problems involved with replete pictorial representations raise the question of whether there is any pedagogical value to these images. However, authors and editors are choosing to mitigate the drawbacks of these images by combining them with text, pointers, and diagrams, rather than eliminating them. This suggests that detailed pictorial representations have some distinctive advantages over other forms of representation such as text and diagrams.

What kind of advantages do detailed images offer? Myers claims that the detail is not informative, but that it does convey the impression that the picture provides immediate contact with reality.[20] If that is all the detail provides, then it might be useful in generating student interest by establishing a sense of personal connection to the depicted subject. If so, then pictorial representations would make a pedagogical contribution through their effect on student motivation, rather than making a cognitive contribution to learning biology. While on this view, the detail is not entirely gratuitous, there is reason to think that it plays a more substantive role in learning biology.

The value of the detail involved in pictorial representation lies in relating detailed information about biological individuals to important conceptual themes. For example, viewing the electron micrograph in relation to a diagram has the potential to do more than convey a sense of immediacy: these images are a key source of evidence for cell structure, and understanding the relation between two different kinds of images involves learning not just to relate the form of an electron micrograph to concepts like "mitochondrion" and other forms of representation of cell structure, but to perform the visual abstraction from the micrograph that is a key to understanding the micrograph *as* evidence for the structural claim.

Lynch's discussion of figures that pair an electron micrograph with a diagram suggests how this works. The diagram has a relatively simple visible form, compared to the electron micrograph. The pairing between a pictorial representation and a diagram with a similar form helps the reader identify which visible features of the micrograph are important through a visual comparison of similar parts of the two figures.[21] This type of comparison can be further facilitated by lines that connect areas in the micrograph with those in the diagram (figure 10.1). The pairing not only makes the pictorial representation more comprehensible, it also relates the content of the diagram to an image that is the result of a mechanical detection process. Understanding the connection between the theoretical content of the diagram and the evidence for those claims as presented in the electron micrograph is essential for understanding biology as a science. Presenting detailed pictorial representations allows students to understand that connection through learning how to make the perceptual links between detailed pictures and abstract diagrams. This is a significant perceptual and cognitive achievement. In a prior paper, Lynch shows that the diagram is not merely a simplified version of the micrograph; relative to the pictorial representation, corresponding parts of the diagram are altered in different ways.[22] These include making some parts of the diagram look more similar to each other than do corresponding areas in the micrograph, and increasing the contrast between other parts of the diagram (relative to the corresponding areas in the micrograph.)[23] The use of detailed pictorial representations thus provides an important resource through which students learn to "see for themselves" how evidence relates to theory.

Another example of how highly detailed images can play a substantive pedagogical role is in the use of replete pictorial representations—especially photographs—to teach students about the diversity of living systems, often a key theme in an introductory biology course. While the details of photos can impede the recognition of salient details in a single photograph, clustering multiple photographs offers an easy way to communicate about differences. Photographs' capacity for detail can be exploited; the overall morphological differences are reinforced by the differences in color, textures, and so forth. So, for example, a section on plants might include a clustered figure of several photographs, chosen for distinctive differences in form.[24] The student can enjoy the aesthetic appeal of the image and soak in the details while being in no danger of missing the main point about how these different organisms relate to one another: they share an ancestor but have significant differences in their traits.



### Schematic Diagrams

Photographs, electron micrographs, and naturalistic drawings all involve different relations between their visible forms and their contents, but all share the general characteristic that detailed visible features convey information about detailed properties of the subject of the image. Diagrammatic representations, on the other hand, involve significant differences in how their forms relate to their contents. Diagrams all share a low relative repleteness. That is, relative to the examples discussed in the previous section, few visible features of the diagram are interpreted as representing features of the subject matter. Diagrams can be sorted into significantly different types, however, and it is the more specific representational features of each type that explain its potential to play a pedagogical role. Two types of diagrams are especially common in biology textbooks.[25]

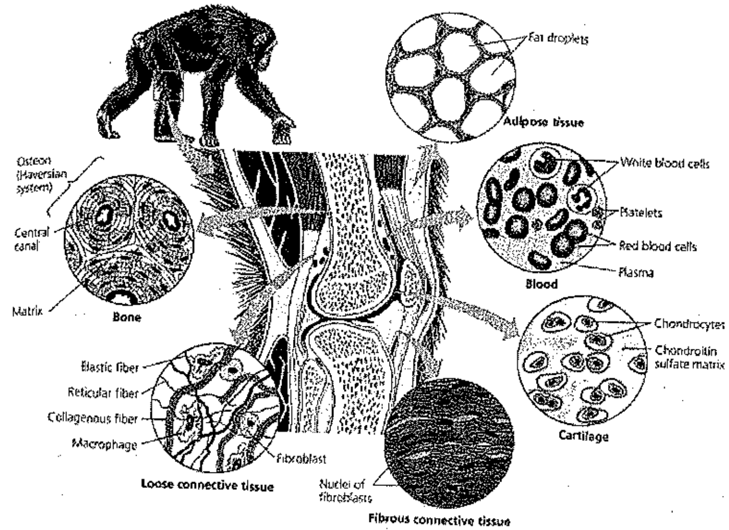
The most common type of diagram in general biology textbooks is characterized by the fact that generic visible features, rather than exact visible details, are interpreted as conveying information, and the information they convey pertains to generic, rather than specific, properties. For example, in the diagram in the right panel of figure 10.1 the visible features that convey information about the structure of the endoplasmic reticulum include lines, shading, and black dots. But it does not represent the endoplasmic reticulum as having ribosomes in exact numbers or in locations corresponding to the locations of the black dots in the diagram; instead, the figure represents generic structural features of the organelle, including representing it as having some number of ribosomes attached. Similarly, it does not represent all endoplasmic reticula as having the specific shape that corresponds to that of the curved lines in the diagram. It is not the exact shape of the curves that conveys information, but more generic properties of the image that convey information, like the curved, contiguous nature of the boundary. Those in turn are interpreted to refer to correspondingly more generic properties, so that this line represents the endoplasmic reticulum as bounded by a continuous membrane. Such diagrams have the capacity to represent features that are shared among many individuals, even though those individuals differ in the ways those features are instantiated.

Above I claimed that schematic diagrams could resolve the pedagogical problems inherent in representing biological structure with pictorial representations. Schematic diagrams are effective in this role for two reasons: first, they are less replete, so there is a reduction in detail and corresponding focus of attention on significant content. This solves the problem of gratuitous detail.

Second, schematic diagrams offer more than mere reduction of detail: they convey a different kind of content than pictorial representations. The nature of their form-content relations provides a way to represent biological classes in cases when the individual members of those classes vary. Images whose form-content relationship involves relating relatively generic visible features to relatively generic properties are especially well suited to representing biological features that vary in how they are instantiated. This offers a solution to the problem raised by Daston and Galison, in which an individual is depicted in detail, which then represents a class whose members vary in those specific properties. Instead, schematic diagrams like this offer a way to communicate about the shared features of a class of objects, even when the individuals of that class vary in how they instantiate those shared features. For this reason, they are very effective means to express generalizations about biological structure.

Schematic diagrams are also very effective means for representing the components of biological systems. This is important explanatory content in biology. One of the key aims of introductory courses is to generate an understanding of biological systems in terms of their material composition, and that is explained in large part by identifying the significant parts of a biological system at a particular level of organization. Diagrams relating components at one level of organization to the next are ubiquitous: they are used to represent organelles as the key components of cells, to show that tissues are composed of cells, how organs relate to physiological systems, and so on. Diagrammatic representation involves an important limitation when it comes to communicating about this key theme. While they are very effective means of representing the components of one level of organization, they are not effective means of communicating about relations among multiple levels of organization, due to limits in space and human visual acuity. While it's easy to make out the component parts of a cell diagram, representation of the component parts of the organelles would make their overall structure less visually prominent. Not only would the structure of, say, a mitochondrion be more difficult to pick out, but in addition, the details of mitochondrial components—the structure






**10.2. Linked schematic diagram.** Fig. 40.2, p. 837, *Biology* 6th ed. by Neil A. Campbell and Jane B. Reece. Copyright © by Pearson Education, Inc. Used by Permission.

of the ATP synthase, for example—would be difficult to see. The size and scaling of the diagram in how it represents the highest level of biological organization imposes limits on the lowest level that can be included and still be discriminated by human visual perception.

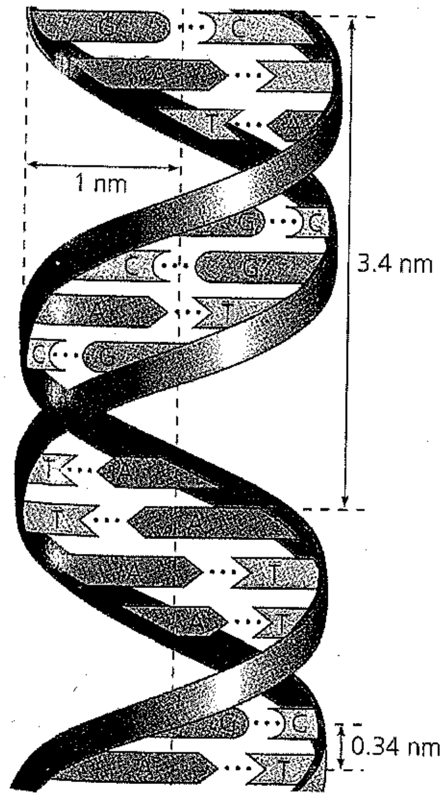
Textbook images rarely push these limits. Instead, textbooks mitigate this limitation in the pedagogical usefulness of schematic diagrams by visually linking multiple diagrams, each of which represents only two levels of organization. A typical kind of figure has a telescoping structure, with a chain of diagrams linking one level of organization to another, which collectively relate multiple levels of organization, from organelle to ecosystem for example.[26] The solution has its own limitations: a telescoping diagram can only trace out a trajectory from one type of cell through one type of organ system, and so on. This technique cannot provide global information about how all the different lower-level structures relate to any one higher-level feature, nor can it show one lower-level structure, like a generic cell, in relation to multiple different higher-level structures. It can, however, relate one kind of biological entity, such as an individual organism, to its component parts, at successively lower levels of organization.

A similar technique can be used to show the structures of several different things at one level of organization, using arrows to indicate that they are components of a wider system. Consider figure 10.2. The arrows in such diagrams are completely arbitrary: unlike the individual structural diagrams at the periphery, understanding the arrows does not involve relating the shape of the arrow to the shape of a biological structure. Instead, the arrow functions as a label, indicating an abstract concept: that one diagram is related to another. Comprehension of this figure depends on understanding the difference in interpretation applied to the arrow compared to the different structure diagrams, including the difference in scaling between the central and peripheral diagrams. Setting aside the question of how students know how to interpret such a diagram, it offers a concise way to summarize the many different kinds of structural relations at one level of organization—that of tissues—and to relate them all to a higher level of organization.

## Compositional Diagrams

There is another form of diagram that appears in all contemporary introductory biology textbooks. Compositional diagrams use a more precise type of relationship between diagrammatic form and content than that which characterizes schematic diagrams. Familiar examples of compositional diagrams include chemical diagrams, electrical circuit diagrams, and some diagrams of biological models, such as diagrams of the Krebs cycle. These are less common in textbooks than schematic diagrams, but compositional diagrams are well suited to convey a different kind of content from schematic diagrams. Figure 10.3 is a typical example. Note that at first glance, it doesn't *appear* to be a different kind of diagram from a schematic diagram. However, the difference is not a matter of the visual appearance of the two kinds of figures, but the ways their visible features are related to their referents. Compositional diagrams are composed of discrete visible elements—atomic characters, like arrows, lines, and other shapes—which are used to refer to things in the same way that names refer: they function as labels. Atomic characters are assigned referents by stipulation, and often have no resemblance to their referents at all. Note the shapes used to represent DNA bases in figure 10.3: those shapes have no similarity relation to the shapes of the bases. The important thing about compositional diagrams is that the spatial arrangement of atomic characters in space is significant: spatial relations among the atomic characters are used to represent relations among the things the atomic characters refer to. In figure 10.3, contiguity between the C, A, T, G shapes on the one hand, and one of the ribbons, on the other, is used to represent co-






10.3 Compositional diagram. Campbell and Reese, 291. Figure 16.5a. Caption: "The double helix. (a) Key features of the double helix. The 'ribbons' in this diagram represent the sugar-phosphate backbones of the two DNA strands. The Helix is 'right-handed,' curving up to the right. The two strands are held together by hydrogen bonds (dotted lines) between the nitrogenous bases, which are paired in the interior of the double helix." From Campbell, Neil A.; Reece, Jane B.; *Biology*, 6th ed., (c) 2002, p. 291. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.

valent bonding of a specific base to the sugar-phosphate chains. Three dots between a C and a G, or a T and A pair, are used to represent hydrogen bonding between bases. Because the length of the "ribbons" is used to refer to the length of the sugar-phosphate chains, the vertical placement of the C/G and T/A shapes along those lengths represents the base pairs as stacked internally between the sugar-phosphate chains.

This feature is quite different from schematic diagrams, which do not use spatial relations in the figure to represent properties of the subject matter in the same precise, systematic way. Recall that they do not represent precise details of system components; a schematic diagram of a cell interior does not represent precise numbers and locations of mitochondria, for example. Rather, mitochondria are represented as inside the cytoplasm—a more generic feature—rather than at specific distances from the cell's nucleus: the spatial relation between the area representing the mitochondrion and the area representing the nucleus is not interpreted as representing the distance between a mitochondrion and the nucleus inside every cell. It is possible to represent details of how organelles might be packed together. To appreciate both the information that is left out in schematic diagrams and the visual difference made by representing the spatial relations among cell components, see David Goodsell's representations of cell interiors.[27] While experts can appreciate the content of such images, the visual crowding takes the visual focus off of the features of the component parts and distinctions among the system parts.

The use of spatial relations to convey specific information about relations among the referents of the atomic characters, however, is what makes compositional diagrams especially useful for conveying explanatory content in biology. Often properties of a biological system are explained by (a) the components of the system and (b) how those components interrelate.[28] Compositional diagrams use atomic characters to refer to the components of the system, and then spatial relations among those characters model the relations among system components that explain system-level features, like why a macromolecule has a particular shape, or the sequence of reactions that relate the different compounds involved in the Krebs cycle.[29] Because they represent very few details about the component parts of biological systems, the focus is on how system components relate to one another. In figure 10.3, for example, there is no information about the structure of the sugar-phosphate chain.

In compositional diagrams, the visible forms of the atomic characters can be chosen on pragmatic grounds, for visual clarity of relations *among* the atomic characters, easy differentiation between different atomic characters, and easy association of each atomic character with its referent. These choices can be made completely independently of how spatial relations among the atomic characters are interpreted, leaving figure designers with a great deal of flexibility in whether there will be any kind of perceived resemblance between atomic characters or not. As a result, compositional diagrams can be used to represent very abstract content because there is no need for the visible features of the atomic characters to resemble any property of their referent.[30] In addition, because the forms of the atomic characters need not represent any of the properties of the system components, compositional diagrams offer a representational format that emphasizes relations among the components of a biological system—in contrast to schematic diagrams, which are most effective at representing characteristics of the components of a biological system. Schematic diagrams also represent generic part/whole relations, but they are most useful for communicating about generic properties of system components and convey little specific information about how those components relate to one another within a biological system.



The capacity to represent explanatory relations among system components, as well as their capacity to convey abstract content, also explains why textbooks frequently use compositional diagrams to convey information about biological processes. For some diagrams, spatial relations refer to nonspatial features, such as the biochemical transitions between two particular states involved in a biological process. For example, diagrams of the Krebs (or citric acid) cycle involve representations of individual carbon compounds connected in a circular form by arrows. Such variation in the *type* of form-content relations involved in a single figure can result in significant confusion for students. While the diagrams of the carbon compounds *do* use spatial features to represent spatial relations (the lines represent bonds between atoms), the circular pattern does not represent a shape or change in location, but rather a sequence of transitions. This has been demonstrated to cause confusion among undergraduates, who interpreted the circular form to indicate that the reactions occur in a circular area.[31] Nevertheless, such a diagram is standard; in spite of its potential for confusion, it highlights the important relations among the component parts of the cycle: the sequential relations between different carbon compounds, and the enzymes that catalyze the successive transitions.

## Conclusion

The study investigated three different kinds of figures in biology textbooks, and analysis of their form-content relations has clarified and explained the pedagogical advantages and limitations of using each of these types of figures in introductory textbooks.

The figures discussed in this paper show that images can provide very effective ways to communicate about biological concepts.[32] In spite of their pedagogical liabilities, replete pictorial representations are common, and we now know that images like photographs and electron micrographs do more than merely convey information about the individual depicted. They play an important function in fostering the inferential move from a detailed representation of the properties of a particular individual—which include many specific properties that will vary from individual to individual—to conclusions about the higher-order structural features that are shared. Schematic diagrams were shown to be extremely effective tools for representing relations between two successive levels of structural organization, and they have the capacity to do so without representing fine-grained details of structure. For this reason, schematic diagrams can communicate the generic features that hold for all individuals at a level without having to choose to represent a class via depiction of a particular individual, with detailed properties that aren't shared. Compositional diagrams use spatial relations to represent functionally explanatory relations among parts of a biological system (figure 10.3). They are excellent tools for representing the relations *among* components at one level of organization that account for structural features or biological processes. In short, images offer significant cognitive value to life science students. The proliferation of images in textbooks is not just a matter of enticing students to engage with the text; rather, the images offer important pedagogical advantages.

## Notes

1. Lorande Loss Woodruff, *Foundations of Biology*, 2nd ed. (New York: Macmillan, 1926).

2. George Gaylord Simpson, Colin S. Pittendrigh, and Lewis H. Tiffany, *Life: An Introduction to Biology* (New York: Harcourt, Brace 1957).

3. This study presents an investigation of the visual representations in the textbook itself; all the textbooks surveyed in this study offer students access to a Web page in which they can view animations, and participate in online activities.

4. Neil A. Campbell and Jane B. Reece, *Biology* 6th ed. (San Francisco: Benjamin Cummings, 2002); William K. Purves, David Sadava, Gordon H. Orians, and H. Craig Heller, *Life: The Science of Biology*, 7th ed. (Sunderland, MA: Sinauer / W.H. Freeman, 2004); Peter H. Raven and George B. Johnson, *Biology*, 6th ed. (Boston: McGraw-Hill 2002). There are changes in image styles over different editions, including a trend among current editions toward more integration of text and figures. I chose to focus on books published from 2002 to 2004 in order to focus on a well-defined, yet recent, time period.

5. Michael Lynch, "The Externalized Retina: Selection and Mathematization in the Visual Documentation of Objects in the Life Sciences," *Human Studies* 11 (1988): 210; Laura Perini, "Explanation in Two Dimensions: Diagrams and Biological Explanation," *Biology and Philosophy* 20 (2005): 265–67.

6. Greg Myers, "Words and Pictures in a Biology Textbook," *The Journal of TESOL France* 2 (1995): 118–20.

7. Laura Perini, "Convention, Resemblance and Isomorphism: Understanding Scientific Visual Representations," in *Multidisciplinary Approaches to Visual Representations and Interpretations*, ed. Grant Malcolm (Amsterdam: Elsevier 2004): 39–42.

8. Myers, "Words and Pictures," 120.



9. Perini, "Convention, Resemblance and Isomorphism," 38–39, 46.

10. Ibid. 43.

11. These are relatively replete pictorial representations; most visible features matter for the identity of the picture. Some images involve a detailed match between a limited subset of visible features, on the one hand, and properties of the referent, on the other, and are less replete. In line graphs, for example, the exact curve of the line represents exact features of the relation the line represents, but line width and color are not informative—those visible details are not meaningful. See Laura Perini, "Diagrams in Biology," *Knowledge Engineering Review* (forthcoming).

12. Laura Perini, "Visual Representations and Confirmation," *Philosophy of Science* 72 (2005): 920–21.

13. Greg Myers, "Every Picture Tells a Story: Illustrations in E. O. Wilson's *Sociobiology*," *Human Studies* 11 (1988): 240–41.

14. John Law and Michael Lynch, "Lists, Field Guides, and the Descriptive Organization of Seeing: Birdwatching as an Exemplary Observational Activity," *Human Studies* 11 (1988): 286–87.

15. Michael Lynch, "Science in the Age of Mechanical Reproduction: Moral and Epistemic Relations between Diagrams and Photographs," *Biology and Philosophy* 6 (1991): 214.

16. Lorraine Daston and Peter Galison, "The Image of Objectivity," *Representations* 40 (1992): 87–96.

17. Ibid. Because those images were handmade, the option to depict an individual that never existed—like an idealized human skeleton—is open. This is not an option for images produced through mechanized imaging techniques (assuming no subsequent manipulation of the image).

18. Myers, "Every Picture Tells a Story," 254.

19. Françoise Bastide, "Iconography of Scientific Images: Principles of Analysis," trans. Greg Myers, in *Representation in Scientific Practice*, ed. Michael Lynch and Steve Woolgar (Cambridge, MA: MIT Press 1990): 196–97.

20. Myers, "Every Picture Tells a Story," 242. This impression is not due to the fact that photos are produced by mechanized processes; Myers notes that naturalistic drawings, due to their "detail and particularity," also have this function.

21. Lynch, "Science in the Age of Mechanical Reproduction," 217.

22. Lynch, "The Externalized Retina," 209.

23. Lynch, "Science in the Age of Mechanical Reproduction," 218. He claims that the diagram performs "gestalt functions," such as those grounding the shift involved from seeing a drawing as a duck to seeing it as a rabbit. I think that this overstates the perceptual shift involved, because the diagram seems to aid more in focusing, allowing for visual abstraction from the micrograph rather than a gestalt perceptual shift. This is a concern because Lynch's formulation may obscure the pedagogical gain involved: If students learn to extrapolate—how to perform their own visual abstraction on new pictorial representations—then they have acquired a cognitively significant perceptual skill.

24. See, for example, Campbell and Reece, *Biology*, 603, figure 30.7.

25. Some pictorial visual representations are non-replete, and thus qualify as diagrams (as I've characterized diagrams.) These images are pictorial due to the very precise correlation of detailed visible features of the figure with specific properties of the referent, but they are also diagrammatic in virtue of relative non-repleteness. Common examples include line graphs in which the exact position of the line is used to represent an exact relationship between two properties, and topographical maps. In diagrammatic forms of pictorial representations, only a small number of visible properties are used to convey information: for pictorial line graphs, only line position, and not width or color, conveys information about the property. This form of representation is used in introductory biology textbooks, but is much less common than the other kinds of diagrams, so I will not provide a detailed discussion of this type of diagram. See Perini, "Diagrams in Biology," for more on diagrams in biology.

26. See for example Purves et al., *Life*, figure 47.7.

27. David Goodsell, Scripps Research Institute, "Molecules in Living Cells," http://mgl.scripps.edu/people/goodsell/illustration/cell (accessed October 24, 2007).

28. William Bechtel and Robert C. Richardson, "Emergent Phenomena and Complex Systems," in *Emergence or Reduction? Essays on the Prospects of Nonreductive Physicalism*, ed. A. Beckermann, H. Flohr, and J. Kim (Berlin: Walter de Gruyter Verlag, 1992): 266–78.

29. Perini, "Explanation in Two Dimensions," 266.

30. The arrows connecting schematic diagrams in figure 10.3 function in this way.

31. T. L. Hull, "Students' Use of Diagrams for the Visualization of Biochemical Processes" (M.Sc. thesis, University of KwaZulu-Natal, South Africa, 2003), which is cited along with other references to works documenting student difficulties with interpreting diagrams in Konrad Schönborn and Trevor Anderson, "The Importance of Visual Literacy in the Education of Biochemists," *Biochemistry and Molecular Biology Education* 34 (2006): 97–98.

32. Indeed, David Sadava, one of the authors of *Life* believes that figures are the *only* effective means of communicating about many of the important concepts in biology (personal communication).

chapter eleven

# Neuroimages, Pedagogy, and Society

Adina L. Roskies

## Introduction

Many lament that the United States is losing its edge in science and technology. A 2007 study reported that 52 percent of Americans believe that the United States is not performing well in math and science relative to other countries, and 64 percent think that the average American is not scientifically well informed.[1] These popular views are bolstered by data from recent studies. The National Science Board's 2006 Science and Engineering Indicators report, which was based on science and mathematics literacy tests administered to high school seniors in 29 developed countries, showed that even the best U.S. students perform near the bottom internationally.[2] There is a general fear that if current trends continue, America will lose its place on the world stage as a scientific and economic powerhouse.[3]

It is not clear to what American decline in performance should be attributed. The American public has not lost interest in science. On the contrary, most Americans claim that science is interesting and important and maintain that it is important that we remain a world leader in scientific development and research.[4] Some of the decline in performance may be attributable to changes in interest driven by cultural shifts, including greater emphasis on material wealth and the cult of celebrity, but most explanations instead focus on the failure of our educational system to adequately prepare students to engage with scientific and technological discourse.[5] The National Science Board's study concludes, "We know—and this report demonstrates—that there is a need to make drastic changes within the Nation's science and mathematics classrooms. If not, our Nation risks raising generations of students and citizens who do not know how to think critically and make informed decisions based on technical and scientific information."[6]