Chapter 10
Deconstructing and Decoding Complex Process Diagrams in University Biology

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Introduction

Students at all levels learn about biology via numerous communication modes: direct experience, oral, text, and representations are but a few. These might include any combination of text, animations, verbal explanations, 3-D models, gestures, and printed images. This chapter explores one particular type of printed image, the complex process diagram. These are diagrams that represent complex biological processes that occur in multiple levels of organization over time. Although complex process diagrams are single static images, they are composites of pictorial, symbolic, and text elements related by devices such as telescoping and arrows, and therefore, they can be considered multiple external representations (MERs), and any findings about how learners interact with MERs may be relevant to this specific representation mode.

Let me first begin with a sketch (Fig. 10.1a) created in my office by a scientist offering to have my first-year university students visit his research laboratory. As he was explaining his research, he spontaneously generated this representation on the whiteboard when words alone seemed inefficient. As an impromptu creation for negotiating shared meaning, it can be considered an inscription. It was not designed to be a self-explanatory, stand-alone representation, rather it evokes a sense that you had to be there and that you need significant background knowledge to understand it. Judging by the common observation of such diagrams in laboratory areas and faculty offices, such inscriptions seem to be an essential communication tool of biologists and biology educators. The adjacent diagram (Fig. 10.1b) from a first-year biology university textbook represents a closely related phenomenon—intracellular calcium homeostasis. Unlike the whiteboard sketch, this diagram was designed to be used without an expert to explain it. The designer of this

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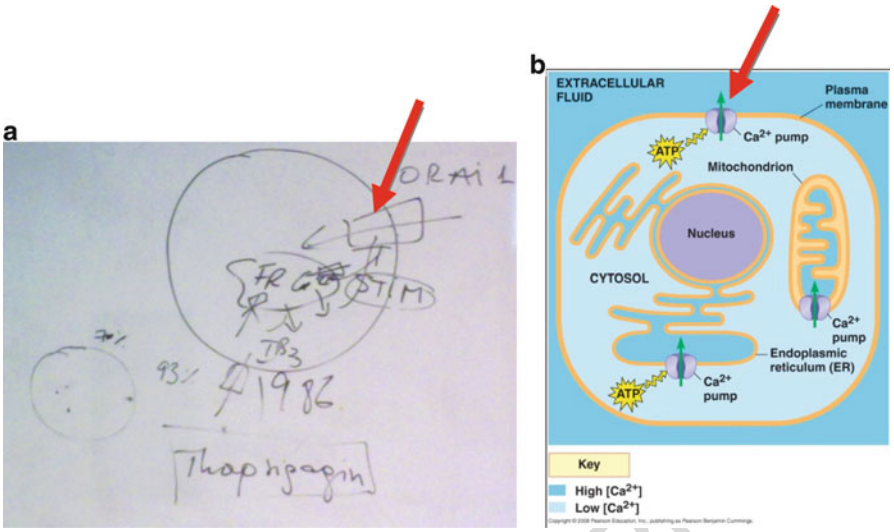

Fig. 10.1 (**a**) A scientist's sketch representing regulation of cytoplasmic calcium. (**b**) Textbook diagram summarizing intracellular calcium homeostasis (Campbell et al., 2008, p. 217). *Red arrows* indicate membrane channel icons (Reprinted with permission)

diagram would have to make assumptions about the audience's prior knowledge of the represented concepts and the meaning of graphic conventions for representing them—such as icons for membrane channels (red arrow in Fig. 10.1b)—as well as about how much detail to include and how much to simplify without compromising fidelity to the accepted scientific model or inviting misconceptions.

How such process diagrams are designed and how students make sense of them during learning is the focus of this chapter. First, semiotics and visual cognition are considered with respect to complex process diagrams. Second, recent research on how students use complex process diagrams is summarized. This chapter concludes with a discussion of the pedagogical implications of the research findings.

Diagrams in Biology

Images are ubiquitous in biology instruction and can take many forms. On a continuum of increasing abstraction, they include realistic images such as photographs, micrographs, and naturalistic art; representational images such as process diagrams, molecular structures, classic experiments, biochemical cycles, and cladograms; and symbolic images such as equations, chemical formulae, graphs, gels, and arrays (Pozzer & Roth, 2003). Content analysis of recent editions of a few representative university science textbooks used in North America showed that approximately one-third of page space is occupied by images. Of the textbooks analyzed, representational and realistic images were most frequently encountered in the biology textbooks,

whereas symbolic images such as equations, formulae, and graphs were the prominent representations in introductory physics and chemistry textbooks (Griffard, 2010a). The ubiquity of complex process diagrams in biology supports the suggestion that biology has a nature and structure distinct from other sciences (Mayr, 1982) and thus may present unique pedagogical challenges for biology educators.

Diagrams are one type of the representational images most frequently encountered in biology textbooks. For the purpose of this chapter, a diagram is defined as any graphic art that is designed to depict or explain how something is organized or how it works. This is more general than some definitions that emphasize geometric or schematic features in which pictorial elements are largely absent. On the contrary, the diagrams encountered in biology often contain pictorial elements that are iconic or semi-realistic, many of which have become domain-specific conventions. For example, rectangular or cylindrical shapes representing membrane transport channels in Fig. 10.1a and b are readily recognizable by biologists. It is interesting and relevant to consider how novices to biology come to understand the meanings of such icons and elements over time.

Complex Process Diagrams as MERs

Rich visual narratives that depict complex biological processes can be considered as complex process diagrams or a type of visual confection because they are "visual events, selected . . . then brought together and juxtaposed on the still flatland of paper" (Tufte, 1997, p. 121). Unlike some graphics designed for other purposes, textbook diagrams have few or no decorative elements (eye candy) or chartjunk; in other words, they have a parsimonious data/ink ratio. Interaction designer Brad Paley recommended that more research be done on how people extract information from various representation modes (Paley, 2008).

An image is considered a complex process diagram here if it meets these criteria:

- Shapes are used to represent biological entities such as organisms, cells, communities, molecules, and membranes; these can be pictorial, realistic, or metaphorical icons.
- Three dimensions are represented, for example, by shading, layering, or parallax.
- Time or sequence is represented with arrows, placement in reading order, or numbered steps.
- Multiple levels of organization are evident by telescoping multiples or exaggeration of scale.

According to these criteria, the MERs in Fig. 10.2 can be considered complex process diagrams. Each is an association of small multiples connected by arrows with different meanings. In the diagram of water uptake in roots (see Fig. 10.2a), gray arrows represent zooming between levels of organization, whereas red and blue arrows represent direction of movement of water through the tissues. In the diagram of blood clotting (see Fig. 10.2b), the arrows signify changes in the blood vessel cross

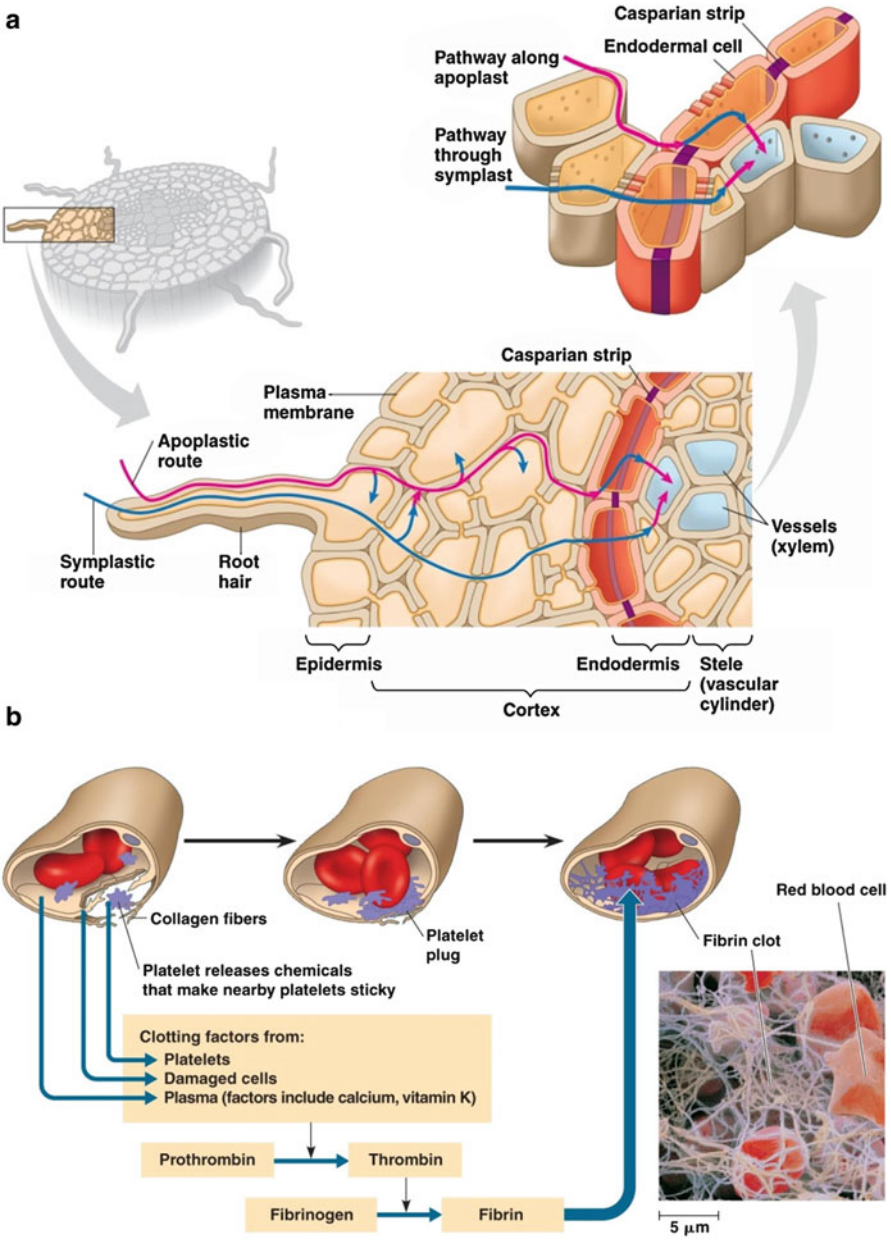

Fig. 10.2 Examples of complex process diagrams illustrating (**a**) water transport into xylem (Campbell et al., 2008, p. 773) and (**b**) blood clotting (Campbell et al., p. 913, Reprinted with permission)

sections over time and sequence in the clotting cascade depicted below them. Complex process diagrams also employ graphic elements such as color, shape, position, and labels to enhance their explanatory power. Some arrow colors are meaningful (e.g., blue for aqueous interior of xylem, red for blood cells), whereas others are arbitrary (magenta for extracellular route, blue for intracellular route). Realistic cell colors, shapes, and layers convey three dimensions, as does the imbedded photomicrograph of a clot.

MERs serve several functions to support learning: They complement, constrain, and construct (Ainsworth, 1999). Static, two-dimensional complex process diagrams can provide these benefits, as can animated, narrated MERs. For example, zooming from macro to micro (roots) and juxtaposing rendered art and real electron micrographs (a clot) provide complementary information about context and ultrastructure, forcing implicit comparison or engagement of more than one cognitive process. Diagrams constrain possible interpretations by focusing the learner's attention to one possible scenario. The images are presented in a reading order (left to right, top to bottom), which suggests a stepwise path by which the learner can construct a linear narrative, complemented by text and scale cues. Therefore, knowing how students use complex process diagrams can contribute to our growing understanding of how MERs function (Ainsworth, 2008; Scheiter, Wiebe, & Holsanova, 2008).

Complex Process Diagrams as Signs

Diagrams can be analyzed from a semiotic perspective, which focuses on the diagram as a sign designed to communicate ideas. Semiotics is the study of signs, which are any images, gestures, sounds, text, models, or textures that communicate information and thus have meaning (Crow, 2003). A sign's meaning as intended by the producer and as interpreted by the user is also considered in semiotic analysis. Iconic shapes and devices such as color coding or layering have to be meaningful. In cell biology diagrams, blobs regularly represent proteins, dots represent ions, cylinders represent channels, and shading represents hollow compartments (Tversky, Zacks, Lee, & Heiser, 2000). Colors take on meaning as arbitrary codes or nonarbitrary metaphors. For example, a popular US university biology textbook (Campbell et al., 2008) uses color as codes: Proteins are purple, lipids are yellow, nucleic acids are red, and aqueous compartments are blue. Process diagrams also rely heavily on arrows to represent a great many aspects of molecular processes (Fantini, 2006), including sequences, gradients, pathways, movement, polarity, increases, and decreases. Furthermore, graphic devices—such as cutaways, zooming frames, and shading—convey depth, scale, and three dimensions.

Because there are common patterns of use and interpretation of the codes that compose signs, diagrams have a visual grammar (Kress & van Leeuwen, 1996). Like the grammar of linguistics, visual grammar is not universal but is culturally influenced and changes with invention and adoption of new codes. This is

especially true in biology, where the enormous expansion of the knowledge base has led to the invention of new icons and devices to represent new phenomena, models, and data, such as those for genomics (Takayama, 2005). There remains a great cognitive distance between abstract external representations generated by these means and the complex process diagrams designed for the general audience. More research is needed to understand how novices to a discipline, such as university biology majors, come to understand these increasingly abstract and domain-specific visual models.

Deconstructing Complex Process Diagrams

The set of marks that compose a printed external representation is arranged in specific positions using ink on a page of paper. One core strategic method in semiotics is deconstructing the marks to interpret underlying meanings (Noble & Bestley, 2005). This representation of the nitrogen cycle (see Fig. 10.3) is an example of a complex process diagram that meets the aforementioned criteria: Iconic irregular shapes represent microbes; three dimensions are evident in shading in the plants, animal, and mushrooms; sequence is represented with arrows to show steps in the nitrogen conversion; and multiple levels of organization are represented by exaggeration of scale of microbes alongside the larger organisms.

First, the marks in a complex process diagram can be categorized as pictures, arrows, or text, each of which has color, size, and position on the background of white space (see Fig. 10.4). In the nitrogen cycle diagram, the semi-realistic pictures represent organisms: an animal (rodent), two plants (different legume species, recognizable by their leaves and pods but with distinct root structures), mushrooms (recognizable by their morphology and the label decomposers), and six white circles containing irregular shapes to represent microbial species. These microbes are not drawn to scale with the other organisms, allowing speculation that their circular white backgrounds were chosen to resemble what might be seen under a microscope. These small pictures are arranged on a background above or below the soil, recognizable by the uneven surface, grainy texture, roots, and darker shading at greater depth. Large arrows on the periphery represent the cyclical nature of nitrogen movement. The blue color was likely chosen for these arrows because nitrogen is generally represented as blue in molecular model kits, for example. Similarly, over a two-page spread in the same textbook, blue and gray arrows are used in the two adjacent diagrams representing, respectively, the water cycle and carbon cycle, whereas arrows in the phosphorus cycle were colored arbitrarily yellow. The arrows within the diagram are shown in various widths to represent relative contributions of each process to the nitrogen cycle. The positions of the arrows on the grid suggest the processes do not occur in a particular stepwise sequence because the processes are ongoing and simultaneous. This is in contrast with sequential processes whose steps are often rendered in positions that are read from left to right and top to bottom (see Figs. 10.5 and 10.6).

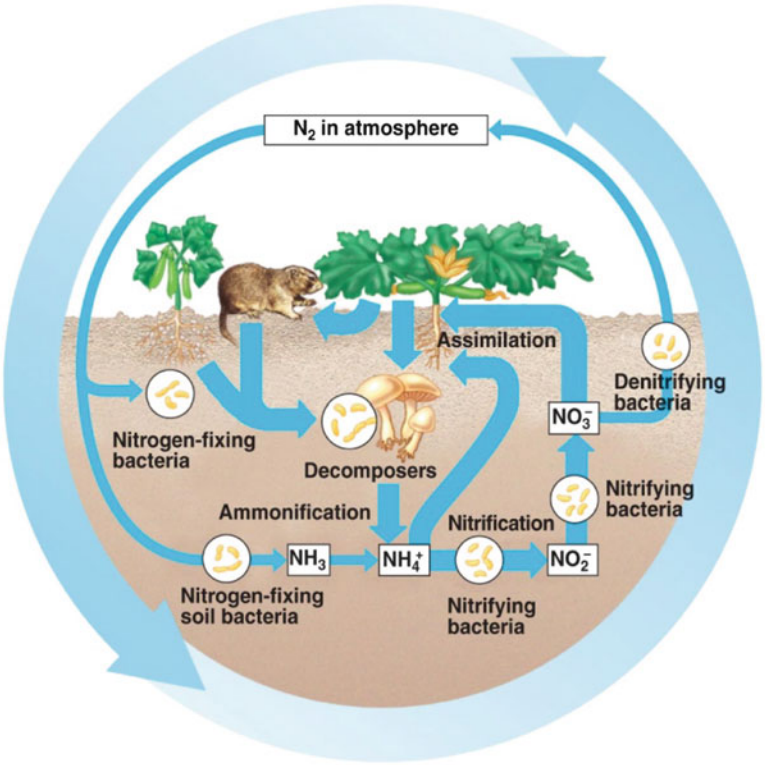

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Fig. 10.3 A complex process diagram depicting the cycling of nitrogen through an ecosystem (Campbell et al., 2008, p. 1233, Reprinted with permission)

The text in Fig. 10.3 takes the form of either labels for organisms and processes or symbols for the relevant chemical forms of nitrogen. None is colored or decorated. Most of these, for example, ammonification and NO_2, require prior knowledge for full understanding of their roles in the represented process. Adjacent to the cycle diagram is a caption with headings Biological Importance, Forms Available to Life, and Reservoirs and Key Processes. In addition to the marks themselves, graphic designers also consider the positions, relative sizes, space use and boundaries of the marks, as well as decision about how much white space to retain. In the diagram in Fig. 10.3, approximately the top one-third of the picture represents atmosphere above ground, presumably to represent the proportion of the nitrogen cycle that occurs in soil.

Graphic designers also practice selective exclusion (Goodsell & Johnson, 2007) to simplify complex phenomenon to its most salient features and "reduce chaos" (D. Mikhael, personal communication, May 30, 2010). This is evident in the nitrogen cycle diagram in that only one representative example of each organism type is shown, and details about the microbial species and their respective

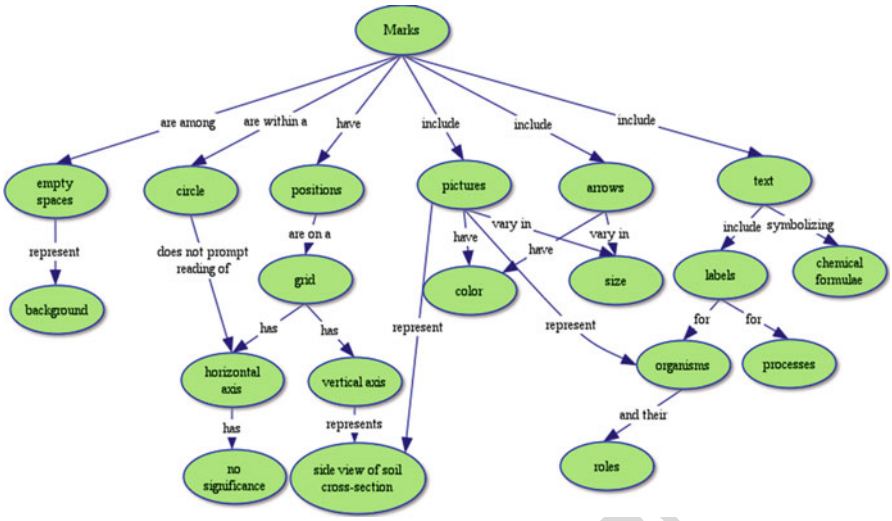

Fig. 10.4 Taxonomy of the properties of the marks composing the process diagram in Fig. 10.3

biochemical processes were omitted. This nitrogen cycle in Fig. 10.3 is the only one in a set of the textbook's (Campbell et al., 2008) four biogeochemical cycles presented with extensive captions. Therefore, this set of four processes can be considered MERs which complement, constrain, and construct readers' understanding of biogeochemical cycles by virtue of their similar codes, proximity, and juxtaposition with explanatory text.

The nitrogen cycle example is first presented for its relative simplicity and its macroscale elements of everyday experience. However, most process diagrams in university biology textbooks, particularly those about cell and molecular processes, contain more elements and require more prior knowledge to decode, for example, the process diagram for microRNAs in Fig. 10.5 from the chapter of the same textbook about regulation of gene expression (Campbell et al., 2008). Unlike the nitrogen cycle diagram, icons here represent polynucleotides, hairpin RNA structures, proteins, and ribosomes that cannot be experienced directly and do not have referents in everyday experience. Nonetheless, molecular biologists recognize these iconic shapes readily. Even the name hairpin and the zipper-like icon have a basis in analogy rather than a direct representation of their three-dimensional structures.

From a careful analysis of the diagram (a) in Fig. 10.5, several assumptions of its graphic designer—about the learner's prior knowledge and familiarity with the representative icons—can be identified as follows:

- Cell structure: the nucleus (internal compartment) denotes a eukaryotic cell
- Nuclear process of transcription and export of the hairpin (textboxes)
- Complementary base pairing by hydrogen bonding that allows the hairpin structure (zipper shape)

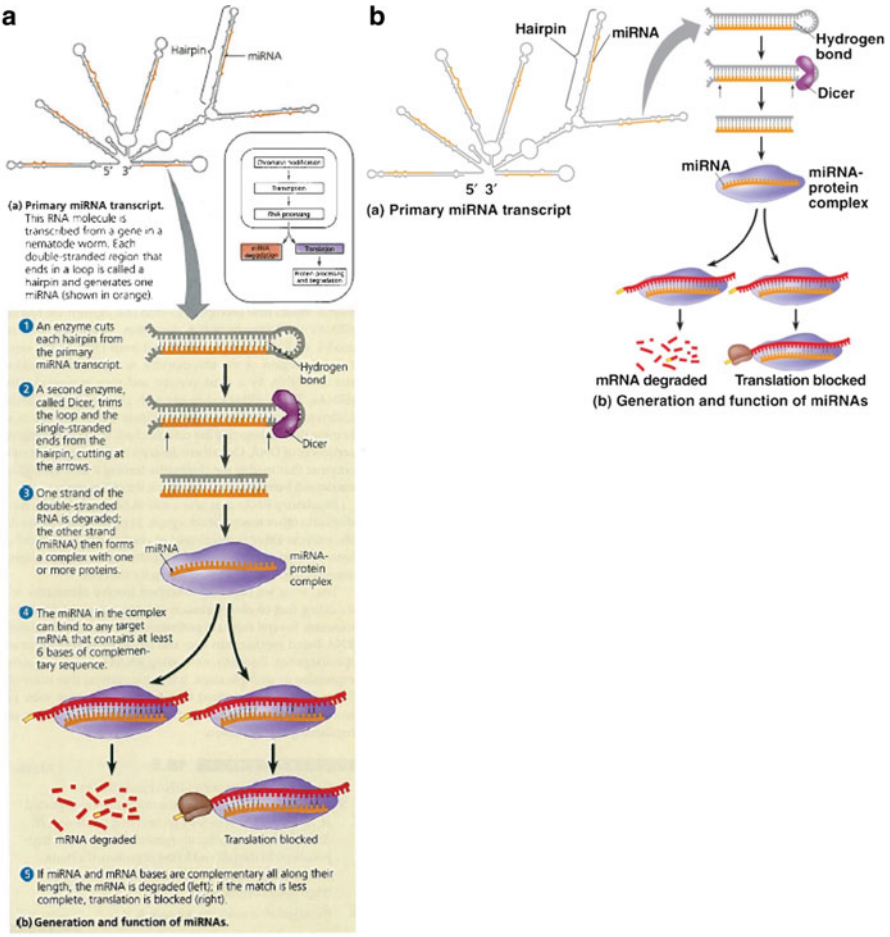

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Fig. 10.5 (**a**) Textbook diagram of the processing of RNA to produce microRNAs (Campbell et al., 2008, p. 365). (**b**) Instructor's version (The instructor's version is not publicly available; it is provided free on CDs for adopters of the textbook.) of the diagram in (**a**) provided by the publisher with fewer orienting and explanatory cues (Reprinted with permission)

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- Enzyme action of dicer (purple scissor shape) 213
- Structure and function of the ribosome (brown realistic shape) 214
- Significance of 5′ cap on mRNA (white tip) 215

Furthermore, significance of color, if any, is often not self-evident. In contrast 216
with the nitrogen cycle diagram, this diagram's vertical orientation is meaningless 217
except as a top-to-bottom reading cue of the sequence. In diagrams for experts, 218
there is significant selective exclusion because of assumptions about the learner's 219
prior knowledge and availability of explanations in adjacent paragraphs. 220

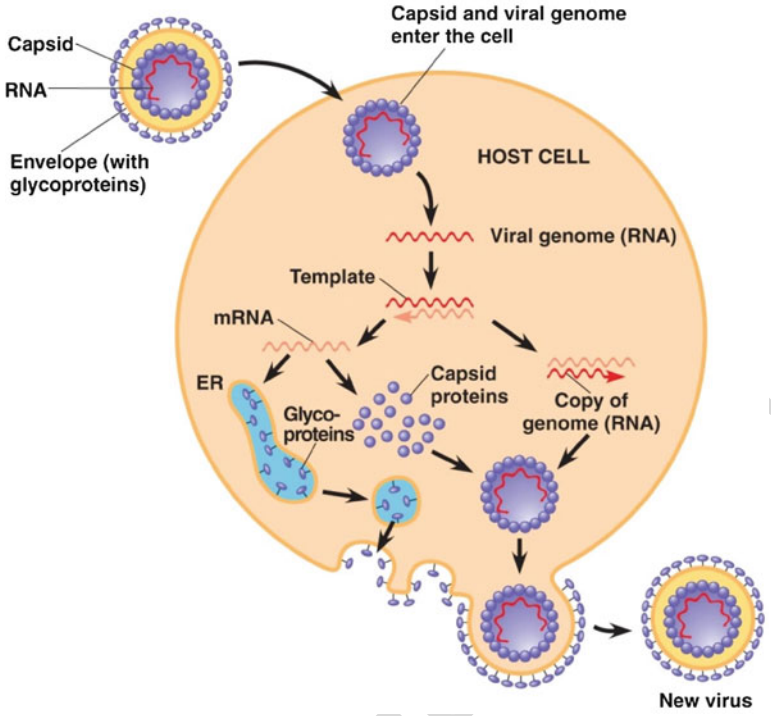

Fig. 10.6 Replication of enveloped viruses (Campbell et al., 2008, p. 388, Reprinted with permission)

The schematic map about regulation of gene expression in the form of a cell (labeled by the red arrow in Fig. 10.5a) recurs throughout the chapter. It provides a metacognitive cue to orient the learner to where this process is occurring in the larger context of the cell. Such orienting icons are also offered in the chapters on metabolism (cell and mitochondria) and evolution (cladograms) and in a chemistry textbook (periodic table) (McMurray & Fay, 2008). This schematic map is not present in the instructor's version for professors (see Fig. 10.5b), nor are explicit textual explanations of the process. It seems that the publisher considered this cue as redundant for professors, but it is not known how commonly instructors might verbally cue students to consider the level of regulation at which this step is occurring.

Semiotics of Production of Textbook Diagrams

Where does the kernel of an idea for a diagram come from and how does the idea evolve into a printed figure in a textbook? A medical illustrator said that when he

was asked to produce a graphic representation of a process, his first step was to research the topic in order to understand it (M. Marion, personal communication, January 16, 2011). In doing so, authors and illustrators certainly encounter features and devices of similar representations and adapt them for their purposes. This suggests that inscriptions in the public domain become signs when their users find them effective, particularly when elements or devices invented by graphic designers come in common usage and take on a meme-like quality. For example, the complex process diagrams of successive editions of competing textbooks—such as 3-Ds, cutaways, zooming, telescoping, color coding, and recurring multiples—can become de rigueur in a short time.

How does a textbook author's design become a part of a widely distributed printed textbook? It involves an iterative process between an author and a graphic artist assigned to the author by the publisher. First, the author generates hand-drawn sketches based on his experiences as a scientist and educator. A graphic artist then renders the sketches and returns the draft to the author for additional changes. After several iterations and both the author and designer are satisfied, editors with additional marketing or cost considerations may suggest further modifications. The artwork may change again after being reviewed by paid consultants from across the US teaching professoriate. It is not known whether students are involved in reviewing the artwork in textbooks, but the existing process seems dependent on assumptions of professors and graphic designers about how learners use and learn from their artwork. More research is needed to identify and test these assumptions with learners and to inform graphic designers about whether their assumptions work. For example, some cladogram designs (phylogenetic trees), although informationally equivalent, engender misconceptions about speciation (Novick, Shade, & Catley, 2011). Serendipitously, several textbook authors have become aware of this finding and changed their cladograms from ladder to tree formats in their first or successive editions (L. Novick, personal communication, January 18, 2011). It is hoped that communication about such research findings to textbook authors and publishers improves the quality of complex process diagrams in textbooks.

The designers of complex process diagrams must make choices about what to include, what codes (colors, icons, and symbols) to use, and the order and placement of elements. All of these require commitments of ink to paper, and some of these commitments are arbitrary. Biology educators teaching first-year university courses encounter learners with a wide range of requisite prior knowledge that is needed to learn from complex process diagrams. Textbooks developed for these learners include graphical cues to grain size, nestedness, and molecular features that would be unnecessary and distracting in representations designed for experts. An informal vertical comparison of high school textbooks to lower and upper level university textbooks supports this. In the progression of textbooks from more novice to more expert audiences, there is an increase in the number of details and icon use and a decrease in the use of semi-realistic icons or orienting cues such as telescoping and color coding. Even when these cues are offered, many go unnoticed without scaffolding (Ainsworth, 2008; Cromley, Snyder-Hogan, & Luciw-Dubas, 2010).

How Learners Use External Representations in Biology

Knowledge of how students use graphic representations during biology learning has come largely from researchers in science education and educational psychology. These studies have focused on how students make sense of representations of biological structures such as antibodies (Schönborn, Anderson, & Grayson, 2002), chromosomes (Kindfield, 1993), and membrane proteins (Dahmani, Schneeberger, & Kramer, 2009) and processes such as membrane transport (Cook, Carter, & Wiebe, 2008), meiosis (Kindfield), genetics (Tsui & Treagust, 2003), antibody activation of T-cells (Cook et al., 2008; Cromley et al., 2010), and evolution (Catley, Novick, & Shade, 2010; Halverson, Abell, Friedrichsen, & Pires, 2009). Kindfield found that more expert biologists exhibited more flexible use of representations of chromosomes and crossing-over than did less expert participants. She suggested that such graphic use skills and conceptual knowledge coevolve or are mutually reinforcing. Tsui and Treagust used the multimedia learning environment *BioLogica* to assess development of genetics reasoning. They found that this MER was effective in improving easier types of genetics reasoning and only when students were engaged. Using eye-tracking tools, Cook et al. found that domain knowledge affected which fields students noticed in a diagram of membrane transport. Those with high prior knowledge looked at the most thematically relevant parts, whereas those with low prior knowledge focused on surface features. More recently, Cromley et al. used think-aloud interviews to categorize the strategies college biology students used when learning about immune function from a text excerpt and its accompanying diagram. They found that students using diagram with text used higher-level strategies such as inferencing and summarizing, whereas students using text only with no diagram used instead lower level strategies like rereading, paraphrasing, and mnemonics. The findings of these studies are consistent with what is now understood about the general nature of expertise (Chi, Glaser, & Farr, 1988) and collectively contribute to the growing body of knowledge about how learners interact with MERs.

AU3

How Students Learn from Complex Process Diagrams

Research is underway to explore how biology students interpret complex process diagrams during learning. My study used in-depth clinical interviews with premedical students to reveal the skills, habits, strategies, and prior knowledge these novices use when decoding complex biology diagrams (Griffard, 2010a, 2010b). Diagrams representing viral replication and muscle contraction were used as cognitive probes in these interviews. (In this chapter, only the viral replication example is discussed due to space limitations.) Neither of these topics was taught in the course; however, subordinate concepts needed to understand the topics had been taught. These included cells, membranes, endocytosis/exocytosis, DNA replication,

transcription, protein sorting, neurotransmitters, gradients, channels and pumps, depolarization, intracellular compartments, microfilaments, and ATPases.

Qualitative analysis of the think-aloud protocols and subsequent debriefing interviews identified several dimensions of representational competence with complex process diagrams. The purposeful sample began with two pairs of participants: selected with respect to English (Abbie and Bob) and Arabic (Alan and Cathy) language high schooling and success in the author's general biology course. A fifth student (Bill) was added when he volunteered to participate; his language of schooling had been English, and he had been moderately successful in biology. Pseudonyms were assigned to the participants such that the initial letter represents their grade in the introductory biology courses: A (Abbie, Alan), B (Bill, Bob), or C (Cathy) on an A–F grading scale, with a median grade of B + for the entire class. In the interviews, each participant was provided one diagram at a time and instructed to "explain in any amount of detail how you understand it." The following protocols illustrate the contrasting explanations of viral replication (see Fig. 10.6) of a more successful student (Abbie) and a less successful student (Cathy):

> Abbie: So we're starting off with a virus I'm guessing, inside a cell, and it's going to enter the cell. It's probably how a virus affects a cell, a host. It shows that when they enter, they lose the coat, so the color is meant to like, yeeah, denote that. And they show different, like how it's going to be changing as it continues to infect and then change over time in the host cell. So you start off with the capsid, then it opens up its coat, then you've got the RNA, the template, the uh the virus comes into the cell, it enters the cell through the membrane, it loses its coat, the viral genome is now replicated due to the, um, the replication that occurs inside the cell. And then you have RNAs used to code for the proteins in the ER [endoplasmic reticulum] as well as the capsid proteins, the new ones that are going to be made. Uh, the ones that are in the ER are expressed on the outer surface of the membrane and then the remaining part of the genome (is still there) [points].
>
> Cathy: This is as written; this is a host cell (reading), ok. And then we have this virus, and this virus is encountered by this cell. And this picture explains the process, like what happens to this virus when it enters this host cell. OK, and I think it's replication of this virus because here you have a virus and here it says new virus, so maybe it's the process, like how it replicates inside the host cell.

These protocols show a trend across all the protocols: More successful students noted many more details in the process and made explicit statements about them, whereas less successful students perceived the task differently and were satisfied with a more general understanding of the process. Given the same instructions to "explain the diagram in any amount of detail," Abbie, Alan, Bill, Bob, and Cathy mentioned, respectively, 10, 11, 10, 8, and 1 of the eleven features in the diagram. Abbie and Alan actively compared, evaluated, and integrated the information gleaned from the diagram into their existing internal representations, whereas Bob and Cathy decoded the diagram at face value by stating propositions that corresponded piecemeal to elements in the diagram. Bill, who had been moderately successful, attended to fewer details than did Abbie and Alan but made comments about this cell in the context of other cells and the process for the organism, extending the represented image beyond the diagram itself.

A semi-structured interview about their think-aloud protocols was conducted in the same session. Participants were asked to elaborate or clarify their meanings and were asked further questions to check for misconceptions. These questions were generally about number, position, color, and orientation of elements in the diagram. For example, participants were asked whether the cell actually sheds a single virus particle as shown or it sheds many particles, represented by a single particle in the diagram. All participants except one correctly assumed one virus particle represented many and that the artist provided only one to keep it simple (selective exclusion and chaos reduction). Bill even chuckled at the notion that the diagram represents replication since production of one particle cannot be considered replication. Only Cathy accepted a face-value interpretation that this single virus particle could be an accurate representation but imagined that a viral infection would be a collective production of single virus particles by many such cells. The participants also were asked whether the position of elements, particularly that of the infecting virus particle, was significant. All responded that the position of virus entry has no top since the cell is a sphere. They understood that the position, as constrained by the ink on paper, was chosen to be at the top to facilitate reading the sequence of events in the process to help them. Each of the participants readily interpreted the significance of color as a code (purple for protein and red for nucleic acid) but overlooked the significance of the yellow membrane surrounding the particles. Taking note of this code would have helped them resolve their question about where the envelope goes when the virus particle enters the cell.

During debriefing, the participants were asked how they used diagrams when studying. Abbie and Alan said that they read the text first so that they could envision the process internally. They then turned to the diagram as a confirmation or check of their internal representation. Bob and Cathy reported going back and forth between the diagrams, as if to use them to clarify the meaning of the text, and vice versa. In this case, their internal representation probably was very similar to the diagram presented. Cathy even reported having somewhat of a photographic memory and could even recall where similar diagrams could be found in her high school textbook. Bill expressed embarrassment that he sometimes took a shortcut when studying by looking first at the textbook diagram before or in lieu of reading the text. In saying so, he seemed to recognize the cognitive value of using both representations actively, as well as the effort required for doing so.

The next phase of interviews was conducted with twelve participants and an additional complex process diagram about the molecular events of seed germination. Preliminary analysis verified that more successful students decoded a complex process diagram in order to understand the germination process rather than to simply read it. In all cases, the participants' attention gravitated first to the familiar features of the diagram, at the expense of attention to contextual cues needed to understand where and why the process was occurring. With adequate wait time, the more successful students noticed the features they overlooked at their first glance and placed the process in a larger context. As in the first phase of the study, more successful students made remarks about familiar features, indicating when they were comparing the external representation with their internal one, again drawing

actively upon their prior knowledge. When they were not sure of something, they looked for additional clues in captions and elements of the diagrams they had overlooked previously, but if they recognized something they had learned previously, they did not commit effort to speculation since this would be easy to look up. This was observed less often in less successful students, who were sometimes distracted by these knowledge gaps.

All of the participants, regardless of whether they had been successful in biology, had similar ability to interpret icons and devices in these diagrams. This suggests that the design of these diagrams was effective for this audience or that the students all became familiar with them in the course of using this textbook. However, depth of interpretation corresponded with how well they performed in the course. Where participants had a strong content knowledge, the arrows, shapes, icons, and colors elicited rich explanatory frameworks in their protocols. However, when they lacked the requisite prior knowledge, icons and arrows could not provide the missing information, such as the significance of the branched arrow in expression of viral RNA. This is consistent with the findings elsewhere that prior knowledge strongly affects what someone finds notable or salient to a problem. Additional studies will be needed to ascertain how novices come to understand the meaning of domain-specific representation strategies, icons, and signs and whether instruction can improve the knowledge resources a learner brings to bear on future tasks.

Dimensions of Representational Competence with Complex Process Diagrams

Kozma and Russell (2005) defined representational competence as "a set of skills and practices that allow a person to reflectively use a variety of representations or visualisations, singly and together, to think about, communicate and act on chemical phenomena in terms of underlying, perceptual physical entities and processes" (p. 131). Based on these findings, the following are proposed as dimensions of representational competence exhibited by the successful students in my study when interpreting complex process diagrams:

- They engage with a clear goal of understanding.
- They notice more details and graphic cues.
- They recognize when they can transfer prior knowledge to the task at hand, including the meaning of graphic elements in the diagram.
- They tap prior knowledge to generate, evaluate, and sometimes discard tentative explanations about the process and the signs representing them.
- They identify and hold in memory what information is missing and look for clues among the available information.
- They attend to cues and devices that can provide information about the larger context in which a process is occurring.

Limitations

This research approach has limitations for answering questions about how novices come to learn to decode complex process diagrams. Although the think-aloud approach is a revered standard in cognition research and an improvement over retrospective verbal reports (Ericsson & Simon, 1993), the very act of converting thoughts to verbalizations changes the cognitive process, and thus, think-aloud protocols cannot be considered a faithful record of internal cognitive processing (Schooler, Ohlsson, & Brooks, 1993). Furthermore, the interviewer's act of asking questions about these features calls attention to features that might not be attended in an authentic learning environment. In addition, any interview strategy that uses textbook diagrams in isolation cannot replicate how students learn from a book in which diagrams are imbedded among elaborative text. These methodological constraints prevent the researcher from making assertions about which codes and signs imbedded in complex process diagrams are noticed and correctly decoded during learning. However, identification of habits and skills is a starting point from which further studies can be designed.

Pedagogical Recommendations for Teaching with Complex Process Diagrams

Complex process diagrams are distinct from other MERs in that they represent processes with many small moving parts that interact over time and space under various conditions and at multiple levels of organization. In consideration of this and the research findings summarized here, the following recommendations for teaching with complex process diagrams are proposed:

- *Engage* with a clear goal.
- *Model* complete decoding.
- Identify necessary *prior knowledge*.
- Consider the *production* process.

Engage with a Clear Goal

Educators should make it clear to their students that the goal of learning with a diagram is understanding, not simply encoding or restating the propositions represented. The intent, therefore, should be generation of a memorable internal representation based only loosely on the diagram used. Using multiple sources (e.g., text, animation, diagrams in comparable textbooks) makes this more likely. Such intent can be conveyed by providing explicit learning goals that incorporate but do not correspond exactly to diagrams in a textbook.

Model Complete Decoding

Educators should cue attention to all details, perhaps by deconstructing diagrams interactively and exhaustively. Educators can scaffold this process by having students systematically identify each graphic element in the diagram and providing effective prompts and adequate wait time for them to learn with the diagram. It is possible that students will have allowed their attention to gravitate toward the familiar, and in doing so, they overlooked boundaries, background color, text, or components within larger structures. This is also an opportunity to explicitly identify devices such as color codes, recurring orienting maps, or domain-specific conventions. For example, instructors can ask students to explicitly state the meaning of arrows. Instructors can ask students to suggest where the represented process is occurring at this very moment in time, such as a predator in its ecosystem.

Identify Necessary Prior Knowledge

When teaching a complex process using a diagram, an educator can informally make explicit the concepts represented in the diagram that students have encountered before in a different context. This will cue students' relevant prior knowledge of content as well as graphic conventions and icons. As students progress from novices to experts, they will encounter more and more domain-specific graphic forms and conventions, and their early explicit attention to these graphic devices will facilitate their automaticity and accuracy in decoding in the future.

Consider the Production Process

Educators can cue consideration of the limits of representations by putting the student in the illustrator's shoes. This can be accomplished by asking why the artist drew only one virus or made the arrows in the cycle so large or left out the nucleus. Instructors can cue students to consider when an artist's decisions about color, number, and position were arbitrary (meaningless) or intentional (meaningful). Lastly, educators can remind students to consider the limitations of graphic analogies. For example, some students may wonder if the proteins would be purple in color or the ATP would flash if they could see inside a real cell. Even when students do not make such egregious decoding errors, attention to the production process serves as a reminder that a representation is the map, not the territory.

In spite of the great pedagogical potential of external representations, visual literacy is often overlooked by educators (Mathewson, 1999; Schönborn & Anderson, 2006). Arguments have been made for the inclusion of visual literacy in science pedagogy (Schönborn & Anderson) and for attending to the development of

representational competence (Kozma & Russell, 2005). As part of undergraduates' acculturation to the disciplines, particularly biological sciences, novices must learn to recognize and understand the elements that compose complex process diagrams and the represented knowledge.

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Author Queries

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Queries	Details Required	Author's response
AU1	Please provide department/division name for the corresponding author.	
AU2	Footnote 1 has been moved to caption of Fig. 10.5. Please confirm.	
AU3	Please check if edit to sentence starting "They found that students. . ." is okay.	
AU4	Please update the reference Griffard (2010b).	
AU5	Please confirm the updated details for the Reference Novick et al. (2011) is appropriate.	