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4

Self-Explaining Expository Texts: The Dual Processes of Generating Inferences and Repairing Mental Models

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Tell me and I forget.
Teach me and I remember.
Involve me and I learn.
—Benjamin Franklin, 1706–1790

The dream of psychologists and educators has always been to identify skills or strategies that can be used across domains. The pursuit of domain-general strategies largely characterized the literature in the 1970s. It was then that general memory strategies (such as rehearsal or method of loci) and problem-solving strategies (such as means–ends analysis) dominated the experimental studies in psychology and simulation research in artificial intelligence. These studies reached conclusions such as the following: Memory retrieval is facilitated when one uses a strategy; memory retrieval improves with age because children are increasingly better at using memory strategies; and experts are better problem solvers because they use sophisticated means–ends strategies (i.e., you find the next solution step by reducing the difference between the goal state and the initial state).

The enthusiasm for domain-general strategies was challenged in the 1980s by work on expertise. This research showed that people with expert knowledge in a particular domain have not necessarily acquired more skillful use of strategies. Instead, it seems that their domain knowledge bypassed the need for general strategies, or else their strategic knowledge is not the source of their superior performance. In the developmental arena, Chi (1978) and Chi and Koeske (1983) showed that young children can remember and recall just as many items as adults in a memory retrieval task if the items are drawn from a content domain in which the child knows something, such as dinosaurs or chess. Likewise, Chi, Feltovich, and Glaser (1981) showed that it is not the use of a means–ends strategy that allows experts to solve problems so readily; rather, experts have richly organized knowledge of the problems (analogous to problem schemata) that allow them to represent the problems in such a way that the solutions became transparent. Hence, experts are not solving problems successfully because they can apply and use strategies skillfully. Rather, the solutions become apparent as soon as they represent the problems correctly. Thus, how well one represents a problem depends on a person's domain-relevant knowledge rather than strategic skill.

Although the aforementioned types of studies challenged the utility of domain-general strategies, in the 1990s, the attention has been turned away from strategies that are effective for performing a task (such as problem solving and remembering) and to the idea that there may be domain-general activities for learning. That is, surely, there may be ways of learning that are more effective and can be beneficial across domains. Engaging in these learning activities might enable some individuals to become experts, whereas others remain novices. In order to differentiate the conventional performance strategies from learning ones, the former are referred to as *strategies*, whereas the latter ones are referred to as *activities*. These two terminologies also fit intuitive notions of strategies and activities. One uses strategies as if they are a kind of rule that can be applied in a particular circumstance, whereas one engages in activities, and the engagement itself promotes learning. These differences, although subtle, are important.

A learning activity that seems to be domain general, effective for learning both procedural and conceptual type of domains, easily used, and beneficial to students of all abilities, was identified and described in Chi, Bassok, Lewis, Reimann, and Glaser (1989) and Chi, de Leeuw, Chiu, and LaVancher (1994). The discovery of this learning strategy hinges on an assumption about learning, which is that new knowledge (whether declarative or procedural in nature) cannot be readily and perfectly assimilated (or encoded) by the student from direct instruction, either in the form of listening to a teacher's explanations, or in the form of reading from a textbook. Instead, the acquisition of new knowledge requires the students to be actively involved in the construction of their own knowledge.

What does being constructive mean? Although the concept of *construction* has been around since Piaget, it has been discussed theoretically in an epistemological way (von Glasersfeld, 1984, 1989) and defined generally as a contrast to either *passive learning* (in which students merely encode and store what is presented) or to *instruction* (in which the research agenda focuses on new ways for teachers to instruct; Papert, 1991). *Construction* is a very broad term denoting both the external behavioral or activity aspects of learning as well as the internal processes of cognitive reorganization (Cobb, 1994).

Evidence for construction is indirect. On the behavioral side, to be *constructive* merely means to be actively doing something while learning. By this definition, engaging in any externally observable activities, such as drawing a diagram, solving problems, answering and asking questions, designing, summarizing, and reflecting, can be broadly construed to be constructive, as opposed to passively sitting there assimilating instruction. Being constructive in this activity sense facilitates learning, as intervention studies have repeatedly shown that students who were required to construct knowledge (by engaging in any of the activities previously listed) learn more and perform better than students who did not actively engage in any of the aforementioned activities. Thus, methods such as reciprocal teaching (Palinscar & Brown, 1984), collaboration (Webb, 1989), or question asking (King, 1992) can all be construed as interventions that engage the students in constructive activities, and such engagement produces more effective learning.

The externally observable activity of construction obviously corresponds to some internal processes of reorganization. Without specifying what these internal processes of reorganization are, one can nevertheless show, again indirectly, that construction occurs. Such evidence comes from studies that show students have alternative conceptions that are qualitatively different from the ones held or taught by the teachers or the textbooks. The existence of misconceptions suggests that these alternative understandings must have been constructed by the learners themselves. Thus, there is abundant indirect evidence showing that engaging in constructive activities facilitates learning, and abundant indirect evidence showing that students do construct alternative conceptions. However, no evidence showed a direct link between engaging in a constructive activity and the processes of reorganization.

The constructive activity to be focused on in this chapter is *self-explaining*, which is the activity of explaining to oneself in an attempt to make sense of new information, either presented in a text or in some other medium. The self-explanation effect, described later in this chapter, provides evidence of a direct link between a constructive activity and knowledge reorganization. The goal of this chapter is to specify what the relation is between the processes of self-explaining and knowledge reorganization. This specification is illustrated by a microgenetic analysis of four self-explanations of a single subject. This qualitative analysis revealed an additional, underlying mechanism of self-explaining the process of revising one's knowledge structure or mental representation. This revision process is to be contrasted with the process of generating inferences, which was the only process assumed to underlie self-explaining in Chi, Bassok, et al. (1989) and Chi, de Leeuw, et al. (1994). (The term *revision* is used henceforth instead of the more general term *reorganization* because the latter term has implications for the more radical kind of knowledge change, commonly referred to as conceptual change. See the later discussion under Two Caveats in the Summary and Discussion section of this chapter.)

The chapter has four sections. The first section introduces and defines self-explaining (Chi & Bassok, 1989). The second section describes the phenomenon of self-explaining in learning a procedural skill (Chi, Bassok, et al., 1989; Chi & VanLehn, 1991) and a conceptual domain (Chi, de Leeuw, et al., 1994). The identification of this phenomenon is complemented with largely quantitative analyses of verbal data. The third section describes an alternative possible process (i.e., revision) by which self-explaining fosters learning and contrasts it with the process entertained earlier (i.e., inferencing). This revision process is proposed as a result of qualitatively analyzing the verbal utterances generated by a single student. The fourth section addresses several additional pertinent issues. (For readers who know the definition and the phenomena, they may skip the Self-Explaining: Definitions and Examples and the Self-Explanation Effect sections.)

SELF-EXPLAINING: DEFINITIONS AND EXAMPLES

Terminologies

Five terms have been used in previous papers to refer to different aspects of the self-explanation research. The term *self-explaining* refers to the activity of generating explanations to oneself, usually in the context of learning from an expository text. It is somewhat analogous to elaborating, except that the goal is to make sense of what one is reading or learning, and not merely to memorize the materials (as is often the case when subjects in laboratory experiments are asked to elaborate). In this sense, self-explaining is a knowledge-building activity that is generated by and directed to oneself. Additional comparisons to elaborations are discussed later.

The generic term *self-explanation* (SE) refers to a unit of utterances produced by self-explaining. That is, it is any content-relevant articulation uttered by the student after reading a line of text. A unit of SE may or may not contain a *self-explanation inference* (SEI), which is an identified piece of knowledge generated in the SE that states something beyond what the sentence explicitly said. Thus, an *SEI* is a piece of new knowledge or inference. This means that for any given SE, a content analysis may reveal several other types of statements besides inferences, such as paraphrases, monitoring statements, and nonsensical statements. (In codings, Chi, de Leeuw, et al. (1994) typically does not differentiate the form of the statement from the content. For example, an inference or a monitoring statement can be phrased either as a question or an assertion.) Because the focus of this research is often only on the content, monitoring statements and questions are counted as an SEI if they contain knowledge inferences. Thus, in general, an *SEI* refers to a specific piece of knowledge within a unit of SE that has been coded as an inference.

The term *self-explanations* (SEs) refers more generally to the entire corpus of collective utterances or verbal protocol data gathered from self-explaining in a particular study. Finally, the term *protocols* is used more generally to refer to any kind of verbal data, including giving definitions or answering questions on the pretests and posttests, as well as SEs.

Examples of Self-Explanations

Examples provide the best way to understand what a SE is. After some examples are presented, additional clarifications are made of what self-explanations are. In the text that follows are self-explanations taken from two different domains. One set of examples is taken from self-explanations generated while eighth-grade students were studying the topic of the human circulatory system from a biology text (Chi, de Leeuw, et al., 1994). The second set of examples is taken from college students self-explaining a worked-out example solution in a college-level physics text (Chi, Bassok, et al., 1989). The sentences in the text are always underlined with an identification of the sentence number such as S17, and the SEs are always in quotes. Student initials are in the parenthesis. The codings on the right tally how many SEIs are coded from the quote, and each SEI is italicized. The following are examples of self-explanations generated by three students after having read the same sentence S17 in the biology text.

S17: The septum divides the heart lengthwise into two sides.

(#1) (AW) " ... the septum, it sort of ... um ... would divide the heart so that you can like ... *distinguish between the two parts.*" —1 SEI

(#2) (BB) "Well, what's a septum? I mean is it, um a *muscle? A bone?* You know, um, *an organ? I don't think it's an organ, though.*" —3 SEI

(#3) (MW) " ... it's probably not like a wall, maybe *like a barrier* ... probably *things can go through it* ... I think it's probably *not like a solid wall.*" —3 SEI

There are several features to notice about these SEs. First, the italicized parts of each SE gives the reader a sense of what constitutes an SEI. Take SE#1. The part that is italicized would constitute an explanation inference because it is stating something that the sentence did not say. The sentence merely discusses the fact that the septum is a divider of the heart in a lengthwise direction. The inference here is that such division allows one to distinguish the two parts. Although this is a commonsense inference (any divider allows one to distinguish the two parts), it is important to make it here because it happens to be an important feature of the heart. (In fact, about one-third of SEIs are generated by bringing in commonsense knowledge. This is discussed again later.) For this SE#1, then, it would be coded as having one SEI. In SE#2, the queries of whether the septum is a muscle, a bone, or an organ, were coded as three SEIs because three separate analogies were made. The last comment, the rejection of it being an organ, could have been coded as another SEI, but it was not in this case in order to be on the conservative side. Instead, it was merely considered to be redundant with the preceding query, analogous to an utterance such as "Is it an organ or not an organ?" In general, the authors tended to be conservative in their coding and not overly attribute any utterance as an inference unless new knowledge is produced.

Notice in SE#3 that when a phrase is repeated, as in the case of *not like a wall* and later *not like a solid wall*, that repetition was generally coded as a single SEI. In this case, the second comment could have been coded as a separate SEI because the adjective *solid* was added. Yet, again, in order not to overly attribute inferences to the student (assuming in this case that wall meant solid in the first place), this SE would be counted as containing three SEIs: it' like a barrier, things can go through it, and it' not like a solid wall.

The next example shows two SEs generated by the same student in sequential order, each after reading the sentences:

S17: The septum divides the heart lengthwise into two sides.

(#4) (NH) " ... so ... there's two sides of the heart and the thing that divides it is the septum, lengthwise." —0 SEI

S18: The right side pumps blood to the lungs, and the left side pumps blood to the other parts of the body.

(#5) (NH) "So, the septum is a divider so that the *blood doesn't get mixed up*, so the septum is *like a wall* that divides the heart into two parts." —2 SEI.

The important feature to notice about SEIs from this example is that they are not necessarily generated on the basis of information confined to a single sentence. SEIs can be an integration across information provided in multiple sentences. SE#4, generated after reading S17, is basically a paraphrase and did not contain any inferences, so it would not be coded as a SEI. However, after reading S18, the two inferences generated in SE#5 integrated information provided in both S17 and S18. That is, S17 talks about the septum being a divider, and S18 talks about the destinations to which blood is pumped from each side of the heart. One of the SEIs embedded in SE#5 is that the septum's purpose is to prevent the blood from the two sides from mixing, a very important inference.

The next example shows SEs taken from attempts to understand a worked-out example taken directly from a college physics text (Chi, Bassok, et al., 1989). The example starts with a description of the problem (which includes a diagram of three strings connected in a knot, with a body of mass *W* hanging from one of the string, as shown in Fig. 4.1). Here, three consecutive SEs by the same student are shown, each given after reading an example statement:

The diagram shows an object of weight W hung by strings.

Consider the knot at the junction of the three strings to be the body.
(#6) *"Why should this [the knot] be the body? I thought W was the body."*

The body remains at rest under the action of the three forces ...
(#7) "I see. *So, the W will be the force and not the body.* OK."

... of the three forces shown in the diagram.
(#8) *"Un huh, so ... so they refer to the point as the body ... "*

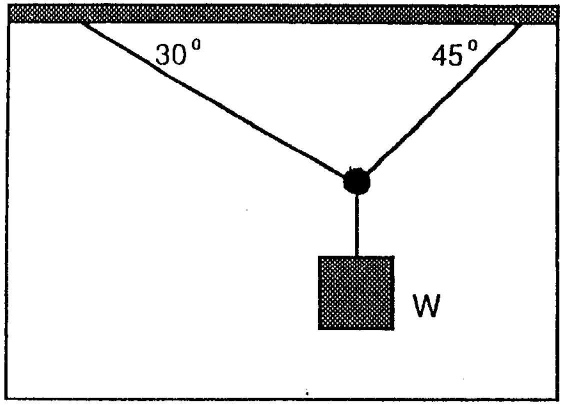


FIG. 4.1. Diagram of the problem with three strings connected by a knot with a hanging block.

Each of the quotes was considered to be a single SE in this earlier study. Note that the student had not realized that the knot (i.e., the intersection of the three strings) was the body because a naive conception normally considers the mass to be the body. Hence, the student had to work through and revise that conception.

Grain Size and Format

The examples of SEs previously presented also illustrate the approximate grain sizes of codings. Earlier, in the physics work, SEs were coded at the level of a sentence or multiple sentences if they referred to the same idea. In the biology study, SEIs were coded at the phrase level. Finally, the biology protocols have also been coded at a more fine-grained proposition level, and the results provided basically the same pattern as the phrase level (see Chi, de Leeuw, et al., 1994). However, because the main interest here lies within knowledge inferences, coding at the grain size of the phrase seems to be more at the knowledge level, and the inference is more sensible, whereas coding SEs at a more fine-grained proposition level sometimes gets redundant. More detailed discussions of coding and grain-size issues can be found in Chi (1997b).

Note, finally, that coding at the knowledge level is independent of coding for the format of the SEs. Coding for the format or structure of the explanations would consist of characterizing whether the student is making an analogy, posing a conjecture, or making a metacognitive statement. The latter two examples can be seen in SE#2, where the student is posing the conjecture that a septum might be like a muscle, a bone, or an organ. The student also rejected his last conjecture. This is a *metastatement*. An analogical SEI can also be seen in SE#5, where the student analogized the septum to a wall. The focus of the discussion in this chapter is not on the format of the SEs, but only on the content.

Context of Self-Explaining

The research on self-explaining has been done in the context of students learning from texts, usually expository kinds of texts on a complex science subject matter. Yet, in principle, self-explaining can be undertaken in any learning context, not necessarily learning from text. For instance, one could self-explain while examining a bus on the street, such as wondering why some buses (the connected ones) have an accordion midsection, as my young son once thought aloud to himself. Basically, *self-explaining* is a process that the learner uses to help himself or herself understand external inputs that can be instantiated in any medium (e.g., text or video). The focus of the discussion throughout this chapter is on learning some new domain of knowledge, with the assumption that there are some external materials that we want the learner to think about and acquire. For the sake of parsimony, a text is referred to as the generic external input.

One could also self-explain or reflect without any external inputs. In this case, it would be like thinking to oneself. Finally, although in Chi's studies students self-explain overtly, in principle, one could self-explain and think covertly. The students needed to self-explain overtly for the pragmatic reason that protocol data can be collected.

What Self-Explaining Is Not

Self-Explaining Versus Talking or Explaining to Others. In principle, self-explaining was differentiated from the act of merely talking because talking may not produce any content-relevant inferences, although in practice, talking often does produce SEIs. However, self-explaining should be a more focused activity than talking: The focus is on trying to understand the learning material and make sense of it, whereas talking is conveying information to a listener. Talking and explaining to others has the added demand of monitoring the listener's comprehension. However, self-explaining and talking and explaining to others do share similarity in that they are both constructive activities and some researchers simply code the amount of talking as a substitute for SEs or SEIs (see, e.g., Teasley, 1995). Another difference between self-explaining and explaining to others is that SEs or SEIs need not be complete and coherent explanations in the Hempel (1965) sense, whereas there is an implicit demand for coherence when explaining to others. For example, suppose one was asked to explain how natural selection works or how a cut heals. Answering either of these two questions would require a coherent explanation, perhaps explicating the causal mechanism, otherwise the explanation would not constitute an answer. A self-explanation is not a complete and coherent answer in this sense. A self-explanation can be partial, fragmented, and at times, incorrect. These differences between *self*-explanations and *other*-explanations are important because they serve different goal: Explaining to oneself serves the goal of revising one's own understanding, whereas explaining to others serve the goal of conveying information. They both facilitate learning, however, probably because they are both constructive activities (see, e.g., findings in tutoring, where the tutors benefit as much as the tutees, probably from having to explain to the tutees, or findings from collaboration research).

Self-Explaining Versus Thinking Aloud. Although one could think of self-explaining as thinking aloud, it is also important to differentiate it from what has traditionally been called *think-aloud protocols* in the problem-solving literature (see Chi, 1997b; Ericsson & Simon 1993). *Think-aloud protocols*, often collected in the context of problem-solving research, is a method of collecting verbal data that explicitly forbids reflection. Think-aloud protocols presumably ask the subject to merely state the objects and operators that he or she is thinking of at that moment of the solution process. It is supposed to be a dump of the content of working memory. The analysis of such think-aloud protocols thereby reveals the search space and search operators that the subject is using. Contrasts between think-aloud protocols and self-explaining utterances are described in greater detail in Chi (1997b). Self-explaining is much more analogous to reflecting and elaborating than to thinking aloud. *Talking aloud* is simply making overt whatever is going through one's memory (see Ericsson & Simon, 1993), without necessarily exerting the effort of trying to understand. Wathen (1997) compared students who were prompted to either talk aloud or to self-explain, and found self-explaining to produce greater learning gains.

Self-Explaining Versus Elaborating. *Elaborating* is a broad concept that was conceived as a strategy. In a memory research context, *elaborating* is a type of strategy that typically asks student to create a relation between concepts or words usually for the sole purpose of remembering the words. In memory research contexts students may create any type of relations between the words, meaningful ones and nonsensical ones. In fact, the more bizarre the elaborated relations between the words are, the more memorable they become. Clearly, this form of elaborating is not self-explaining, presumably because nonsensical relations would not lead to learning.

Elaborating has also been studied in the context of learning. In learning contexts, if students fail to elaborate, the researcher can then undertake two options: A researcher can either insert elaborations into the text to see if (and which ones) enhance learning, or, a researcher can instruct subjects on how to elaborate. Thus, whereas elaborating is an intervention either a researcher can undertake (by inserting inferences into text materials) or a strategy a subject can undertake (to create relations and embellishments between either concepts or sentences), self-explaining, on the other hand only makes sense if it is undertaken by a subject. This is because self-explaining is assumed to be a generative process in which subjects construct their own idiosyncratic elaborations. Thus, from a self-explaining perspective, one can assume that inserting uniform elaborations into a text would not be beneficial to every student.

Notice that students' interpretation of what they are supposed to do under a self-explaning instruction may not be fundamentally different from what they do under a general elaborating instruction. The instruction used to prompt students for self-explanation is as follows:

> We would like you to read each sentence out loud and then explain what it means to you. That is, what new information does each line provide for you, how does it relate to what you've already read, does it give you a new insight into your understanding of how the circulatory system works, or does it raise a question in your mind? Tell us whatever is going through your mind—even if it seems unimportant.

Thus, although there may be some differences in the instructions given to the subject about elaborating versus self-explaining (especially in the extreme case when students are asked to generate meaningless and bizarre elaborations), from the learner's point of view, conventional elaboration and self-explanation instructions may be more or less the same. The difference lies mainly in the researcher's conceptualization of them. To be succinct and contrastive, one could say that elaboration researchers conceive of elaborations (either supplied by the experimenter or the learner) as serving the purpose of improving an imperfect text, whereas self-explanations should be thought of as serving the purpose of improving one's imperfect mental model (or representation). Thus, in the imperfect mental model view, it would not make sense to have the researcher or experimenter supply the elaborations. Alternatively, one could say that self-explanation is a form of elaboration (only the ones that are supplied by the learner), but not all elaborations are self-explanations (because some elaborations include the ones supplied by the experimenter). These differences are further discussed later.

The Self-Explanation Versus the Generation Effect. The self-explanation phenomenon is reminiscent of the generation effect discussed in the 1970s (Slamecka & Graf, 1978). The *generation effect* is a phenomenon uncovered in a traditional paired-associate memory test. The design is for subjects to either read word pairs such as *rapid- frequent*, or for the subjects to generate the associated word given the stem word, an initial letter, and a rule. So, suppose the rule is synonym, and the stem and initial letter given are: *rapid-f*. In this generation condition, the subject was asked to generate the associative word on the basis of the rule and the initial letter. In this case, the majority of the subjects would generate the word *fast*. It turns out that memory for the associated words are significantly better if they were generated rather than simply read.

Actually, a more related study to the self-explanation effect is one by Stein and Bransford (1979), who studied subjects' memory for a target word embedded in a sentence, such as "The *fat* man read the sign." Recall is tested by the sentence frames with a blank for the target word *fat*. Consistent with traditional elaboration research, they elaborated each sentence frame with additional information, such as "The fat man read the sign that was two feet high" or "The fat man read the sign warning about thin ice." As expected, recall was better for elaborated sentences than nonelaborated, fostering the traditional view that elaborating a text can help memory. However, the more important finding was that if the subjects were asked to generate elaborations themselves, then their recall was even better. This suggests that providing one's own elaboration somehow facilitated access. The generation effect in the context of memory retrieval and the self-explanation effect in the context of learning share one thing in common: They are both constructive activities. To that extent, they facilitate memory retrieval and learning, possibly because being generative means one is being more attentive and actively laying down memory traces.

Self-Explanation Inferences Versus Other Types of Inferences. How are SEIs different from other types of inferences? SE and SEI can be thought of as knowledge inferences and can be contrasted with four types of inferences that are commonly studied in the psychological literature. First, SEI is not a bridging type of inference, the kind commonly studied in the comprehension literature. A *bridging inference* is one whereby a referent is explicitly provided. For example, if a sentence had referred to the septum as *it*, and the student explicitly refers to it as *the septum*, then that is providing a bridging inference. By our analysis, such bridging inference provides no additional knowledge about septum, so it is not counted as a piece of knowledge inference. Second, an SEI is not a paraphrase because paraphrasing often does not add new knowledge, as shown in SE#4. Third, an SEI is not a logical-type of inference, as the kind commonly studied in the psychological literature on inferencing from quantifiers, such as "All men are mortals, if John is a man, is John a mortal?"

A fourth commonly studied inference is *schema-based inferences*. *Schema-based inferences* refer to the supply of inferences based on prestored knowledge. In many ways, one cannot call these inferences; they are more analogous to retrieval of prestored knowledge. For instance, consider if a reader was asked to read the following sentences:

(S1) <u>John sat down and talked to the waiter.</u>

(S2) <u>Five minutes later, the food arrived.</u>

An inference that is needed to comprehend S2 is that John had ordered some food. Such an inference can easily be supplied by the reader. To do so, the reader merely activates and retrieves a prior script. One can ascertain that this piece of missing inference in the text is already a prestored piece of knowledge because we can ask the reader, prior to reading such sentences, what one does in a restaurant, and the reader will typically say that a diner sits down, orders food, eats, and pays the bill. Thus, prior to reading, the reader already knows the script or schema for what happens at restaurants; so that from the perspective of the text, this is an inference, but from the perspective of the reader, this is not an inferred piece of new knowledge. In reading expository text, often about unfamiliar science topics (as in Chi's studies), one can assume that an inference is constructed and not retrieved.

To recap, SEIs have been contrasted with four kinds of inferences commonly studied in the literature. SEIs are unlike all of them in that SEIs are pieces of new knowledge constructed or generated by the students. How these knowledge inferences can be generated when the students are learning a new domain is considered later.

THE SELF-EXPLANATION EFFECT: THE PHENOMENON

In this section, two of Chi's studies showing the self-explanation effect are briefly described. The two studies were carried out in two different domains, in biology (on a passage about the human circulatory system consisting of 101 sentences) and in physics (chap. 5 of Halliday & Resnick, 1981, on mechanics). The details of these studies have been published elsewhere, so the goal here is to highlight their similarities and differences for comparison purposes, and more importantly, to address the crucial individual differences that exist in both sets of data.

The Physics and the Biology Studies

The design of the two studies are basically the same. Each study has three phases. The *pretest* phase consists of some kind of assessment of both the students' prior knowledge about the domain topic and some indication of their general ability. The *learning phase* consists of studying the text (or examples in the text) and explaining while they study. The *posttest phase* consists of a postlearning assessment, always taken 1 week later to make sure that the learning was long term. The design of both studies are laid out in Table 4.1. The Chi, Bassok, et al. (1989) study is referred to as the physics study, and the Chi, de Leeuw, et al. (1994) study as the biology study

The differences between the two studies are laid out in Table 4.2: acquiring declarative (system-related) knowledge versus procedural knowledge; using eighth-graders versus college students as subjects; explaining expository text versus worked-out example solutions; answering questions in the posttests versus solving problems. The most important difference between the two studies is that in the physics study, the self-explanation effect was obtained by encouraging students to spontaneously generate SEs, whereas in the biology study, students were prompted (thus enforced) to self-explain.

TABLE 4.1
The Design of the Biology & Physics Studies

Biology	*Physics*
I Pretest Phase: Assess Prior Domain-Specific Knowledge & Ability	
• Define 20 terms	• Read first three chapters & target chapter to a criterion
• Answer half of the questions	• Bennett's Mechanical Comprehension Test
• Draw diagram	
II Learning Phase: Read and Explain	
• 101 sentences	• 3 examples
• Answer prompts for function of 22 components	
III Posttest Phase: Assess Learning	
• Define terms	• Solve isomorphic problems
• Answer all of the questions	• Solve end-of-chapter problems
• Draw diagrams	

TABLE 4.2
Differences Between the Biology & the Physics Studies

	Biology Study	*Physics Study*
Domain:	Declarative (the circulatory system)	Procedural (mechanics)
Age:	Eighth graders	College students
Learning Task:	Explain expository text	Explain examples in text
Assessment of Learning:	Answer questions	Solve problems
Experimenter Elicited Explanations:	Yes, by prompting	No, spontaneously generated
Control Group:	Yes	No

A second important difference was that the biology study had a control group of students who were not asked to self-explain, but were asked to read the same text twice. Reading the text twice took about as much time as reading it once along with self-explaining.

The Findings

In reporting the results, the unit of analysis for the physics study was at a coarser grain than the biology study, primarily because the students in the physics study were not enforced to self-explain. This means that whenever they did explain, one only had to judge whether what students said contained ideas relevant to and extending beyond the materials they were studying. Every relevant and extended idea was counted as an SE. In the biology study, on the other hand, because the students in the prompted group were enforced to self-explain after every line, this meant that they could have just stated nonsense, so one had to decipher whether there was an SE inference within each articulation. This required a meticulous coding to determine whether an SEI was embedded in each articulation. The way an SEI was coded has already been discussed in the previous definition section. To put it another way: In the physics protocols, whenever a student voluntarily said something, what they said was either an SE or not an SE, in which case, the utterances could either be some kind of metastatement ("I don't know what's going on here") or some kind of mathematical statement. In the biology protocols, because the students were enforced to self-explain, there were lots of utterances, but only some of them were SEIs.

Individual Differences or Range of Self-Explanations Generated. In both studies, there was a continuous range in the number of SEs generated by the students, although in the one case, it was generated spontaneously and in the other case, it was enforced. In the physics case, the average number of SEs generated by each student while studying a worked-out example problem ranged from a low of less than 2 to a high of more than 25. The number of SEIs generated in the biology case ranged from a low of 7 to a high of 111 for the entire passage of 101 sentences on the circulatory system. In both cases, it was a continuous range rather than a bimodal split, although the analyses often refer to the students as either high or low explainers.

Learning Correlated With the Number of Self-Explanations. In both studies, learning correlated with the number of self-explanations generated: That is, the greater the number of self-explanations generated, the better the students learned. Instead of correlating the number of self-explanations generated and the number of problems solved correctly (because of low *N*), an analysis based on a median split of the number of SEs generated shows that in the physics study, students who

generated, on average, 16 SEs per example solved 86% of the problems correctly, whereas students who generated on average 3 SEs per example solved only 42% of the problems correctly. All differences to be reported here are statistically significant. Henceforth, students who generated a large number of explanations, on average, are considered to be the *high explainers*, whereas students who generated fewer number of SEs are referred to as the *low explainers*.[1]

The correlation between learning and self-explaining can be seen in two ways in the biology study. First, students who were prompted to explain learned more than students who were in the control group (those who were not prompted to explain, but did read the text passage twice). The prompted group gained 26% from the pretest to the posttest on answers to the assessment questions, whereas the control group gained only 16%. However, such difference in the amount of gain between the two groups is impressive considering that: (a) this passage is taken from a very well-written text; (b) the control group read the passage twice; and moreover, (c) there undoubtedly were some spontaneous (albeit covert) explainers in the control group as well; and most important, (d) the difference between the two groups gets more pronounced on the harder questions. This last result suggests that the prompted explainers understood the materials more deeply than the nonprompted group of learners. This means that generating self-explanations per se was beneficial, assuming that the self-explanations generated contained inferences.

A second way to show the benefit of self-explaining is to contrast the high and the low explainers within the prompted group. As in the physics result, the high explainers (i.e., those who generated, on average, 87 SEI) in the biology study learned considerably more than the low explainers (i.e., those who generated, on average, 29 SEIs). The high explainers answered significantly more questions correctly (78%) than the low explainers (61%). This difference again became even more pronounced for the harder questions. Notice that Wathen's findings (1997) replicated this result in that her prompted to self-explain group learned more than the group who was simply prompted to talk aloud. One could interpret her result to mean that

[1]Note that if the numbers reported here vary slightly from the published report, that is because here, the results are reported in terms of *high* and *low explainers*, whereas the published paper (Chi, et al., 1989) reported the results in terms of the *successful* and *less successful* solvers. In the original study, a median split was done on the basis of the number of problems solved correctly, then the number of explanations generated as the dependent variable was considered. Here, the students were divided into two groups on the basis of the number of SEs they generated, then the number of problems they solved correctly were compared. Because the results are correlational, the pattern of the data is the same.

talk-aloud did not generate as many knowledge inferences as self-explaining, so that the talk aloud group is comparable to the low explainers.

The individual difference results in the number of self-explanations generated, either spontaneously (in the physics case) or enforced (in the biology case), raise two important questions. On the surface, the intervention question one immediately thinks of is how one can encourage students (the low self-explainers) to generate more SEs or SEIs. However, a deeper question might be why some students generated more SEIs than others. Understanding the processes of self-explaining (to be discussed in the following section) may shed light on understanding this why question.

Taken together, the results of the two studies show that generating self-explanations per se is useful for enhancing learning because the prompted group learned more than the unprompted group in the biology study, and the high explainers (whether spontaneous or enforced) learned more than the low explainers in both studies. Moreover, the more inferences the students' self-explanations contain, the better they learn. This suggests that generating self-explanations is useful in general (because it is a constructive activity), but it is even better if one could encourage students to generate SEs that contain lots of inferences. In order to understand whether or not this can be done, one needs to understand the processes of self-explaining that can account for such individual differences.

Robustness and Generality of the Phenomenon. Although findings of the self-explanation effect are primarily correlational, the phenomenon is robust because many other researchers have found similar results, using a variety of manipulations and research designs. Moreover, the domains that other researchers have explored expanded beyond the ones Chi studied (mechanics and the circulatory system) to include different domains such as learning LISP coding (Pirolli & Recker, 1994), electricity and magnetism (Ferguson-Hessler & de Jong, 1990), and probability (Renkl, 1997). It has been shown that self-explaining is effective for both college students and eighth-graders, and Siegler (1995) has extended this to 5-year-olds, in the context of asking them to explain the experimenter's reasoning for a number conservation task.

The Influence of Prior Knowledge and Ability in Understanding the Self-explanation Effect

Before advancing reasons for why and how self-explaining works in enhancing learning (to be discussed in the third section of this chapter), one

should first consider what can cause individual differences in the amount of self-explanations generated. Assuming that all students have the goal of trying to learn (at least, in the context of a laboratory study), two possible factors, prior knowledge and ability, are tentatively rejected.

Prior knowledge can be divided into four types: *domain-specific knowledge*, *domain-relevant knowledge*, *misconceptions*, and *domain-general world knowledge*. *Domain-specific knowledge* refers to knowledge that is directly related to the content of the materials. Prior domain-specific knowledge was controlled first in a general way (e.g., by selecting students who had not taken college courses in the relevant topic) and then assessed more specifically in a number of pretests. In the physics study, domain-specific knowledge was controlled and assessed in the following ways. First, students were selected to participate in the physics study only if they had a specific kind of profile, such as not having taken any college physics courses, but having taken one high school physics course. Second, to equate for the amount of knowledge students gained from the first three chapters of the physics text, all students had to master the materials by being able to solve the problems at the end of each chapter to a preset criterion. Otherwise, they had to reread the chapter and re-solve the end-of-the-chapter problems. Third, to assess how much knowledge they did acquire from the expository part of the target chapter 5, they were asked to define Newton's three laws after they read that part of chapter 5, but before they self-explained the worked-out solution examples. Similarly, prior domain-specific knowledge about the circulatory system was assessed by having the students define terms in the pretest, prior to reading the passage, to see if they knew, for example, that the atrium is a chamber of the heart. Sometimes, students were also asked to draw the path of blood flow, as well as answer some pretest questions. Hence, prior domain-specific knowledge was usually thoroughly assessed in multiple ways.

In both the biology and the physics studies, there were no differences between the high and the low explainers in terms of their prior domain-specific knowledge. For example, in the biology study, there were no significant differences in the pretest scores between the prompted group (39%) and the unprompted group (42%). Likewise, in the physics study, the most sensitive prior specific knowledge assessment was the definition of Newton's three laws. Newton's three laws were scored by decomposing each law into three to five subcomponents. Thus, prior to the study of the examples embedded in chapter 5, both the high and the low explainers scored 5.5 of a possible 12 components for their definitions of Newton's

Laws. Overall, in both studies, there were no noticeable differences among the students in their prior domain-specific knowledge.

A second type of prior knowledge is *domain-relevant knowledge*. This refers to general knowledge that is relevant to understanding the domain under study (as in the circulatory system), such as knowing that distance is inversely related to pressure or that lungs are proximal to the heart, as opposed to domain-specific knowledge such as knowing what a septum is. These latter two pieces of knowledge are relevant for making inferences and understanding why only the pulmonary vein has no valves because lungs are so proximally close that the pressure coming from the heart will remain high for such a short distance. In a current, unpublished, study (see Chi, Siler, Jeong, Yamauchi, & Hausman) a posttest of domain-relevant knowledge was administered to students after they learned the unit on the human circulatory system, and again, no differences were found between the high and low explainers in their domain-relevant knowledge in the context of tutoring.

A third kind of prior knowledge is the amount of *misconceptions*, or false beliefs, that students initially possess. This knowledge is the complement of students' domain-specific knowledge. That is, domain-specific knowledge assesses what correct knowledge about the human circulation a student knows. False beliefs and misconceptions assess how much incorrect knowledge the student has about a domain. False beliefs are of the type such as believing that the heart oxygenates blood, and misconceptions are of the type such as conceiving of heat as a kind of substance rather than as a kind of process. Although data are scant, the physics data show that high explainers have fewer initial misconceptions (10.0) than do low explainers (13.3), as assessed by a test presenting problems and questions of the kind "Which car will suffer more damage in a head-on collision, the heavy Cadillac or the small Volkswagen?" In the biology data, the high explainers also had slightly fewer initial false beliefs (2.25) than did the low explainers (3.00). However, neither differences reached statistical significance (perhaps because of the low *N*), although they were both in the right direction, so one would have to conclude that the number of misconceptions and false prior beliefs do not correlate with the quantity or quality of self-explanations generated.

What about *domain-general world knowledge*? One way to assess domain-general world knowledge is to consider tests such as the California Achievement Test (CAT) as a measure of domain-general knowledge. Again, in the biology study, there were no significant differences in the CAT scores of the students of the prompted (87%) versus the unprompted (83%) groups. If one assumes that the CAT measures one's general knowledge, then again, one can conclude from these results that general world knowledge did not correlate with learning from self-explaining. Thus, none of the measures of the four types of prior knowledge could have predicted differences in learning from self-explaining.

What about ability? Can it be a cause of differences in the amount of self-explanations generated? *Ability* was assessed in a number of different ways, such as by students' grade point averages (GPAs). In general, there were no differences between groups in their general profile, such as the number of science courses taken, or the GPAs. Within each group, ability was further assessed by specific tests. In the biology study, if one wanted to consider CAT as a measure of ability, then one could differentiate students on the basis of their CAT scores and show that those who scored higher on the CAT (98%, with 0.8 *SD*) did not benefit more from self-explaining than did those who scored lower on the CAT (72%, 17.4 *SD*). Both groups gained about 35% from the pretest to the posttest.

Ability in the physics study was assessed by the Bennett Mechanical Ability test (BMA; because it correlates with success in domains such as physics). The assumption was that scores on this kind of test would predict ease of learning physics-related materials. There was absolutely no difference between the successful and less successful solvers in their performance on the BMA test. Both groups scored around 22 to 23 points out of a possible 29 for the mechanical test.

In general, these results suggest that individual differences in the number of self-explanations generated is not due to prior knowledge or ability. Prior knowledge has been examined in terms of prior domain-specific knowledge, prior domain-relevant knowledge, prior false beliefs and misconceptions, and prior general world knowledge (if one considers the CAT to be basically a measure of general world knowledge). In all these cases, there were no significant differences in any of these measures between the high and the low explainers. Thus, it appears not to be the case that students who self-explained more often have more prior knowledge or have higher ability. Rather, it appears that the mere act of self-explaining fosters greater learning.

TWO CONTRASTING APPROACHES TO UNDERSTANDING THE SELF-EXPLAINING EFFECT

Why does self-explaining facilitate learning? To say that self-explaining has a positive effect on learning because it is a constructive activity fails to explain the internal processes or mechanism of construction and the fundamental individual differences result, that some students generate more SE inferences than others (whether spontaneously or enforced), and thereby learn more. Thus, the ideal explanation needs to identify the processes of self-explaining such that the processes also account for the finding of variance in the amount of SEIs generated.

The internal processes corresponding to self-explaining were tacitly implicated in the way the SE protocols were coded in the two earlier studies. The perspective taken in these earlier analyses conceived of self-explanations as the product of self-explaining. That is, self-explaining was conceived of as a constructive activity that generated inferences, and these inferences were determined on the basis of information that was missing from the text sentences (thereby missing in one's mental model). Thus, the perspective taken in the earlier work (Chi, de Leeuw, et al., 1994) was to think of self-explaining as the process of generating inferences. This perspective made three implicit assumptions: The text is incomplete, the goal of self-explaining is to generate inferences to fill the omissions in the text, and the omissions in the text correspond to the gaps in one's mental model, thus implying a direct correspondence between the model conveyed by the text (henceforth referred to as the *text model*) and the learner's mental model. That is, the inference-generating perspective implicitly assumed that learning is directly encoding materials presented in a text, and the result of the encoding is a mental model that is isomorphic to the text model. When the text is incomplete, generating inferences will fill gaps in one's encoded mental model.

The inference-generating view was supported in three broad ways: by the success in the coding method, by the empirical results, and by the postulation of inference mechanisms that showed how it was plausible to generate new knowledge without being told (either by the text or by an agent, such as a teacher). With respect to the coding method, it has already been shown how coding was undertaken, how an utterance was counted as a self-explanation if it contained knowledge beyond what the text sentences stated. Thus, SEs were treated as a product (the inferences) of self-explaining. Although the inferences were capturable externally in the SE protocols, it was assumed that they were stored and internalized in the mental representation as well. In this view, a direct link between a constructive activity (i.e., self-explaining) and the external results of some internal processes (i.e., the inferences) was established. The implicit assumption was that these generated inferences filled gaps in the students' mental representations, much as they filled omissions in the text. Obviously then, a mental representation that contained more inferences (with fewer gaps) had to be better than a mental representation with fewer inferences (and more gaps). Despite the fact that this inference-generating perspective was able to establish a direct link between a constructive activity and the resulting product (a more enriched, correct, and coherent mental model), this perspective cannot explain why some students generated more SEIs than others. The following details this perspective and then presents an alternative perspective.

Generating Inferences: The Incomplete Text View

The hypothesis that self-explaining is the process of generating inferences beyond information contained in the text sentences tacitly assumed that the text is incomplete in some ways. There are two kinds of incomplete text: a *poorly written text* and a *well-written text*. A *poorly written text* can be incomplete in missing anaphoric references and/or connective links between sentences, thus destroying structural coherence. Making a text more structurally coherent facilitates comprehension in general for all learners (Kintsch & Vipond, 1979). A poorly written text can also be explanatorily incoherent (Kintsch & van Dijk, 1978), in the sense that some crucial piece(s) of background information is left unstated. When crucial pieces of information are left unstated, not surprisingly, subjects with high-domain knowledge can supply their own, so that they learn just as well from an explanatorily incoherent text, but low-domain knowledge subjects obviously profit more from having this explanatory background information supplied (McNamara, Kintsch, Songer, & Kintsch, 1996).

However, the kind of texts used in Chi's studies are typically very well-written and coherent, ones that have been popular and used frequently in the classrooms. Thus, an incoherent text is not the source of learning failures. Moreover, an incomplete text is not necessarily an incoherent text. Nevertheless, even if a text has both structural and explanatory coherence, it can contain omissions. Thus, even well-written texts can be incomplete because they cannot possibly contain all the information that can be conveyed about a topic. For instance, suppose we assume that for each component of the circulatory system, such as a valve or the atrium, there are three dimensions that a text can discuss: its structure, its function, and its behavior. For example, for the valve, a text can describe how it is made (like a flap of tissue), what its function is (to prevent blood from going backward), and what its behavior is (closing and opening depending on the pressure created by the blood flow). Similarly, a text passage can also describe the structure, function, and behavior of the atrium. Yet, typically, for each component, not all three dimensions are mentioned in the text. In the text passage used in the biology study, the functional dimension is omitted about half of the time. Yet, aside from these first-order features about the components, a text can also describe the relations between a feature of one component and a feature of another component. For example, the text could describe the relation between the behavior of the atrium (contraction and relaxation) and the function of the valve. Again, the majority of these kinds of second-order relations are omitted. Besides the second-order relations, one can also imagine the text explicating third-order relations, such as the relation between a feature of a component (such as the function of the atrium) and the overall goal of the circulatory system, such as the relation between the need for the atrium to act as a temporary reservoir in order for blood to circulate with a sufficiently high pressure. Knowing this kind of relation allows a student to answer complex *why* questions, such as "Why should the valve of the atrium close for a short time?" Again, these kinds of third-order relations are hardly ever mentioned. Thus, from this simple exercise of analyzing the omissions in our circulatory text passage, one can only conclude that all texts are incomplete, without necessarily being incoherent structurally or explanatorily. Thus, it seemed natural to assume that the source of learning failures is the omissions existing in a text, even if it is well written.

Is an Incomplete Text Detrimental to Learning? The preceding example of an incomplete text, one that omits some information about the topic, was illustrated in the context of a science text. In principle, it is no different from narrative texts, as was seen in S1 and S2. In a narrative text, much information is omitted as well. However, in a *narrative text*, presumably the reader has the prior knowledge to make the correct inferences, whereas, it was not clear how students could generate inferences when they lack the appropriate prior schemata and scripts (to be discussed in the next section). In this section, the empirical evidence that supported the assumption that self-explaining is generating inferences of omitted information is recapped. The empirical evidence gives indirect, direct, and causal support.

Indirectly, the results cited earlier showed not only that explainers learned more than nonexplainers, but also that high explainers learned more and deeper than did the low explainers. That is, the high explainers not only could answer more questions correctly in general, but they also excelled particularly in the hardest questions. This confirmed an *inference view* because this view assumes that inferences fill gaps in one's representation, so that the more enriched one's representation is, the better one has learned.

The inference view was also supported directly by showing that students were able to induce information omitted from the text (such as the function of an atrium). For example, in SE#5, the student correctly induced the function of the septum, as a device to separate the right and the left chambers. Similarly, in SE#2 and SE#3, the students were trying to induce the structure of the septum, which was again not stated explicitly in the text. To confirm that students were, in fact, trying to induce the omitted information, the students' knowledge of the functions of 11 components was explicitly assessed during the reading phase (Chi, de Leeuw, et al., 1994). The assessment consisted of asking the students to explain what the function of each component was shortly after they had read and self-explained a sentence describing a particular component. The high explainers were significantly more successful at correctly inducing the functions of components (10.5 functions out of 11 components), whereas the low explainers were less successful (7.8 out of 11).

Finally, the inference view was supported causally by the way the questions were constructed in the biology study. That is, many of the questions posed to the students (such as the *why* questions) required knowledge of the function of the components in order to answer them correctly. This probably allowed the high explainers to be better at answering the hardest *why* questions than the low explainers since the high explainers had succeeded at inducing a greater number of functions of components.

Thus, it seemed clear that the information omitted from the text was necessary for deep understanding, as assessed by the students' ability to answer the missing functions of components, as well as the *why* and other types of complex questions in the biology study. However, because students seemed to be able to *recover* this information by self-explaining, their success reinforced the view that self-explaining serves the purpose of inducing the omissions in the text. More generally, the incomplete text, corresponding to an incomplete mental model view, persisted, with the availability of indirect, direct, and causal empirical evidence.

Inference-Generating Mechanisms for New Knowledge. An incomplete text view assumes that self-explaining plays the role of filling omissions in the text and that the text model and the mental model are isomorphic in that they both contain the same gaps. If self-explaining is the process of generating inferences to fill gaps while learning a new domain, then one needs to postulate what kind of mechanisms can generate inferences when there is no prior knowledge or schemata. That is, what kind of inferencing mechanism can generate new knowledge to facilitate learning a new domain aside from comprehending inferences that make a poorly written text more coherent (such as supplying the anaphoric referents) or inferences from prior scripts and schema, because these are assumed not to exist for learning new domains. Several inferencing mechanisms can be postulated that can account for learning a new domain without prior knowledge.

First, students can produce inferences by integrating information presented across different sentences (as shown in the SE#5, where SE#5 integrates information contained in S17, relating the septum as a divider to information contained in S18 that the different sides of the heart pump to different locations in the body, therefore, the septum must serve the purpose of preventing blood from mixing).

Second, inferences can be generated by integrating information presented in sentences with prior (commonsense world or domain-relevant) knowledge, using processes of analogy or any kind of comparison to integrate them. Once a comparison is made, then attributions can be made about the new information on the basis of the properties of the analogized entity. SE#3, shown earlier, exemplifies both of these types of inferencing processes. In SE#3, the inference that the septum is not like a wall was generated by analogizing the septum to some kind of nonwall-like penetrated barrier (commonsense world knowledge). Moreover, once the idea of a penetrated wall is retrieved, then the septum is attributed with the possibility that things can go through it.

A third way of generating inferences is to use the meaning of words to imply what may also be true. Again, SE#1 illustrates this. In that SE, the septum is inferred to *distinguish between the two parts. Distinguishing between the two parts* might be an inference derived from the semantics of the word divide. That is, one often divides things so that there are two discrete subparts. So this might be an inference generated from the meaning of the word *divide*.

Fourth, an inference can also be generated by combining any of these inferencing mechanisms. Various permutations of combinations of the previous three inferencing mechanisms can be proposed. The next self-explanation illustrates the combination of using inferencing from the meaning of a word with inferencing from using commonsense knowledge:

S22: In each side of the heart blood flows from the atrium to the ventricle.

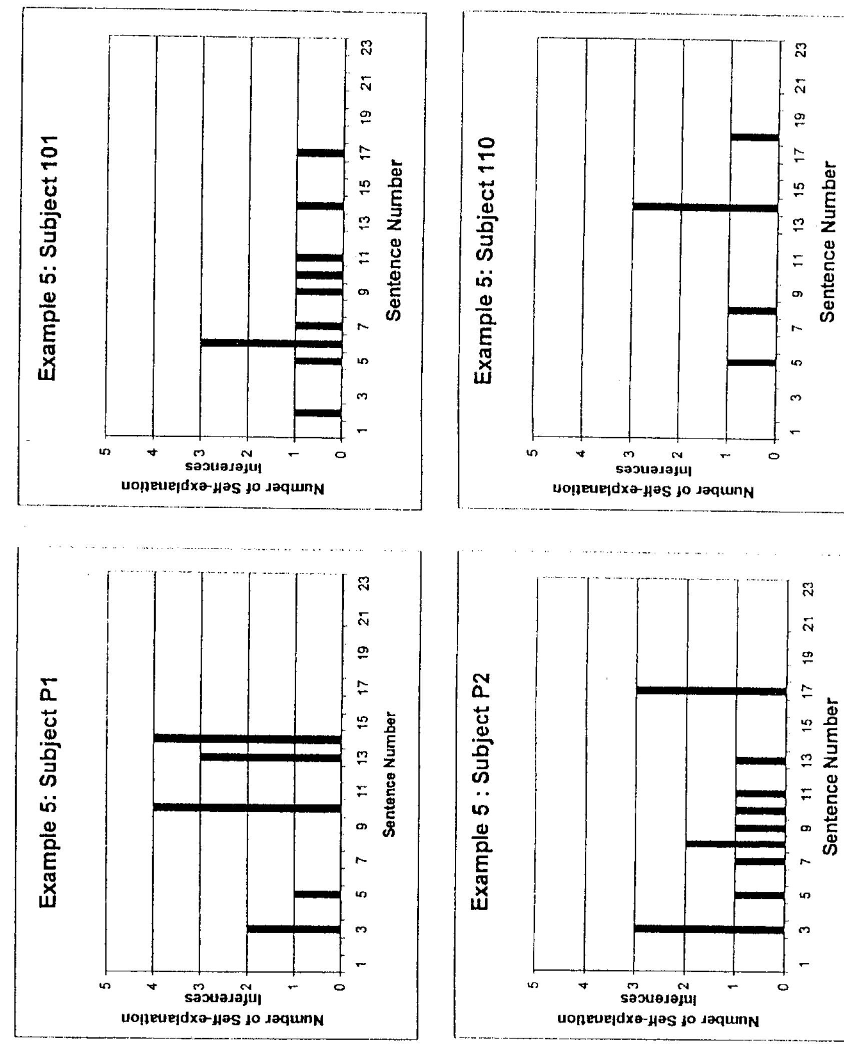
SE#9 (DA) "Well, so that, ... um ... the heart, the, *the atrium is up on the top and the ventricle's on the bottom, ...* "

Here, the idea in the text stating that blood flows from the atrium to the ventricle may have activated the commonsense knowledge that liquid-like entities can only flow from a higher to a lower position (due to gravity). Hence, if blood flows from the atrium to the ventricle, then the atrium must be above the ventricle. Thus, in this case, the word *flows* activated the context in the real world under which such situations can occur, leading to the inference that the ventricle must be on top.

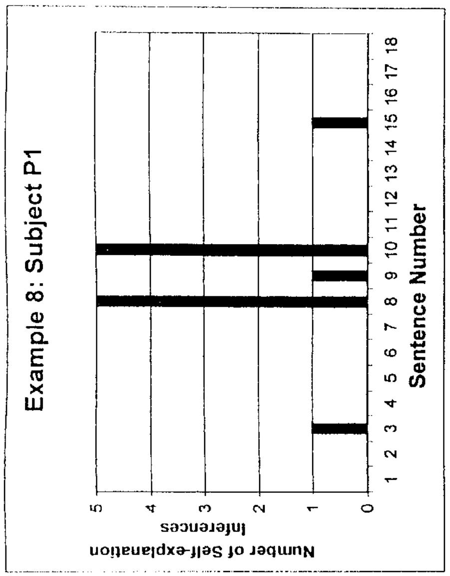
Two important conclusions can be drawn from these analyses. First, one can conclude that several knowledge-inferencing mechanisms can be postulated, and that they can be instantiated in the protocol data. The inference mechanisms just illustrated make it plausible to see how learning a new complex domain can occur when the learner simply attempts to connect new knowledge with prior knowledge, even if the prior knowledge is nondomain-specific, commonsense world knowledge. Thus, postulating these mechanisms takes the mystery out of understanding how learning can occur by self-explaining. The possibility that these three types of inferencing mechanisms (along with their combinations and variations) can construct knowledge that is needed and missing from the text reinforces the view that self-explaining is an inference-generating process. Second, one can conclude that via these mechanisms, using largely commonsense background knowledge, one can learn a new domain of knowledge without being taught. That is, one can learn by explaining to oneself, using one's existing knowledge, without having someone else (a more knowledgeable person) explain to us. These two conclusions seem sound, well grounded, and counterintuitive, thus lending credibility and popularity to the self-explanation effect.

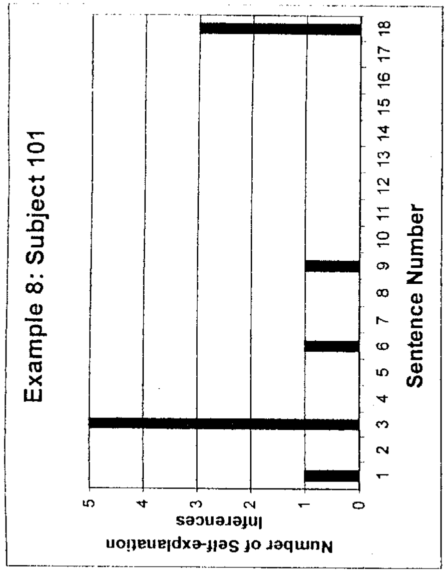
Skepticisms About the Inference-Generating View. The preceding section assumes that self-explaining serves the purpose of inferring missing information not explicitly stated in the text sentences, so that information in the text served as the context by which self-explanations were interpreted. This particular view was derived by an analysis of the missing information in the text. This view was then further reinforced by the success in coding for inferences in the self-explanations that were not stated in the text, and further supported by indirect, direct, and causal empirical findings. Finally, this view was further bolstered by the postulation of a variety of plausible inferencing mechanisms that can generate new knowledge in a learning context. However, if generating inferences of missing information is the only mechanism underlying self-explaining, then it should predict several additional secondary results.

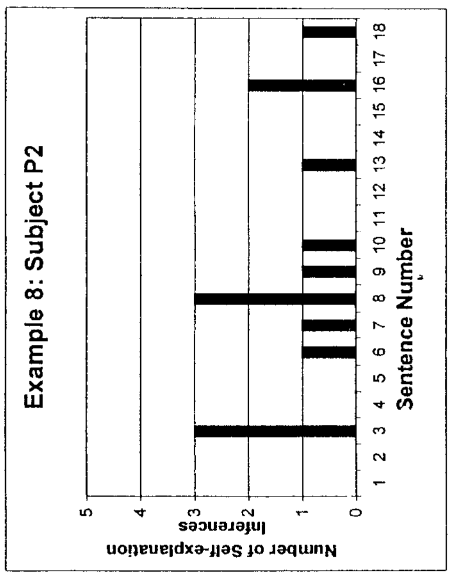
First, a content analysis of any well-written text from a normative point of view, as discussed earlier, will show omissions of information distributed throughout the text passage. Thus, in principle, if self-explaining was generating inferences, one would expect a uniform distribution of self-explanations throughout the text sentences. However, this prediction was not supported. Figures 4.2a and 4.2b show the distribution of self-explanations for the four high explainers, taken from the data collected in the Chi et al. (1989) physics study, for Examples 5 and 8. (Without being redundant, only two of the three examples are shown when data of individual subjects are presented.) Instead of a uniform distribution of a small number of self-explanations across all the sentences in the example, the self-explanations seem to be clustered at several key locations. Yet, these key locations cannot be the sites at which crucial information was missing due to explanatory incoherence because there is little consensus in the loci at which the majority of self-explanations were generated by each student. For example, in studying Example 5 in the text (Fig. 4.2a), subject *P1* spontaneously self-explained four idea units at Sentence 10, whereas the other three high explainers did not self-explain much in that location. Figure 4.2b shows a similar lack of consensus in the loci for Example 8 from the physics text. Figures 4.2c and 4.2d show the distribution of the four poor learners. Again, although the poor learners generated far fewer spontaneous self-explanations, they nevertheless show the same pattern of nonuniform distribution across the sentences of an example. The same pattern can be seen in the biology study in which students were enforced to self-explain. Here, one can simply count the number of lines students uttered, just to get a quick look at the distribution. For the best learner (Fig. 4.2e), although there is a baseline of explanations distributed across all the sentences (because they were required to self-explain in this study), there is nevertheless a pattern of spikes occurring unpredictably across the sentences. The same pattern can be seen for the poorest learner (Fig. 4.2f). Thus, it does not appear to be the case that self-explanations were generated to correspond to information omitted from the text.

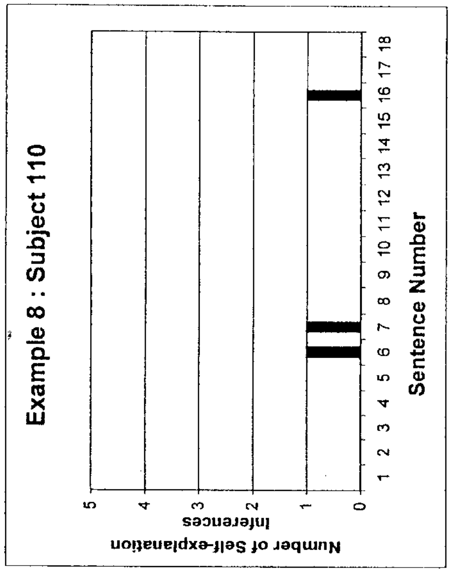


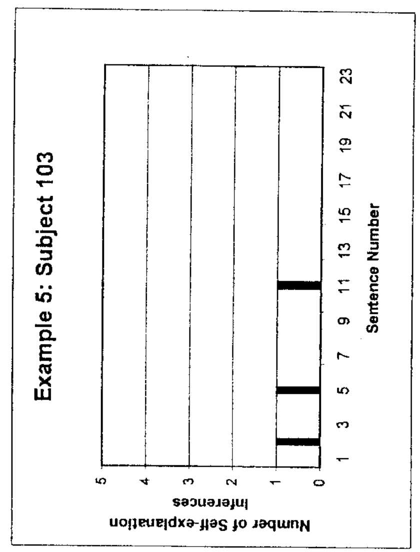
(a)

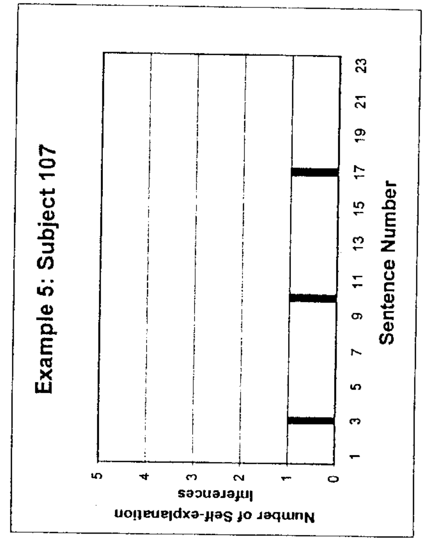

Example 8: Subject P1
Number of Self-explanation Inferences
Sentence Number

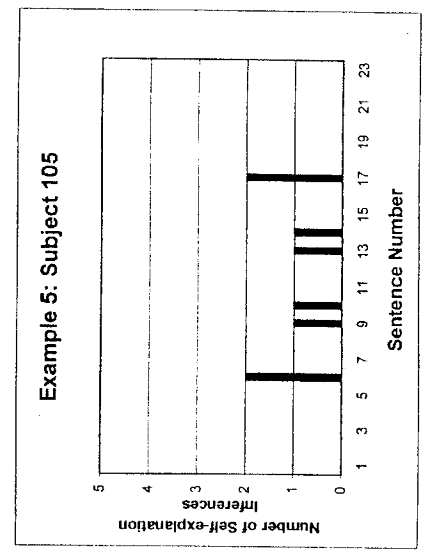

Example 8: Subject 101
Number of Self-explanation Inferences
Sentence Number

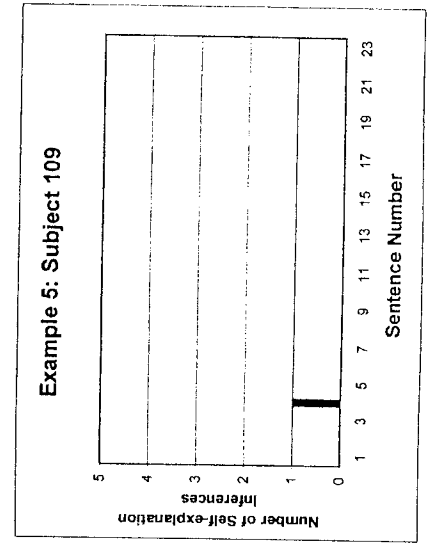

Example 8: Subject P2
Number of Self-explanation Inferences
Sentence Number


Example 8 : Subject 110
Number of Self-explanation Inferences
Sentence Number

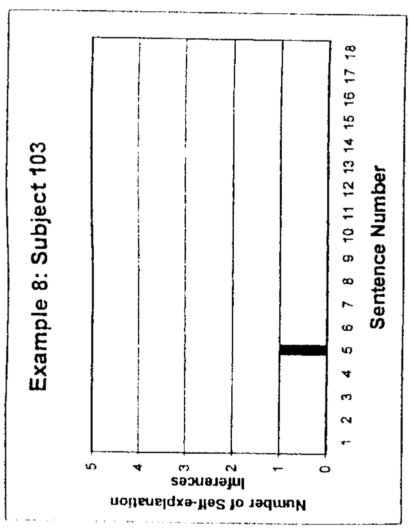

Example 5: Subject 103
Number of Self-explanation Inferences
Sentence Number

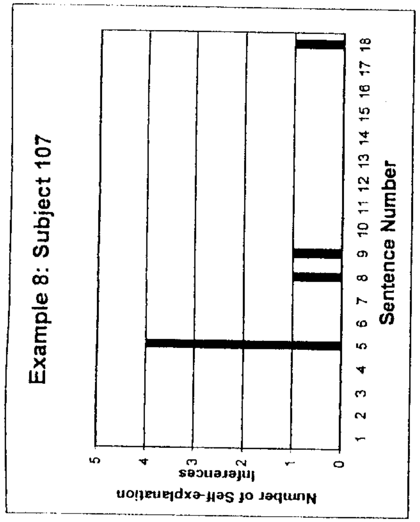

Example 5: Subject 107
Number of Self-explanation Inferences
Sentence Number

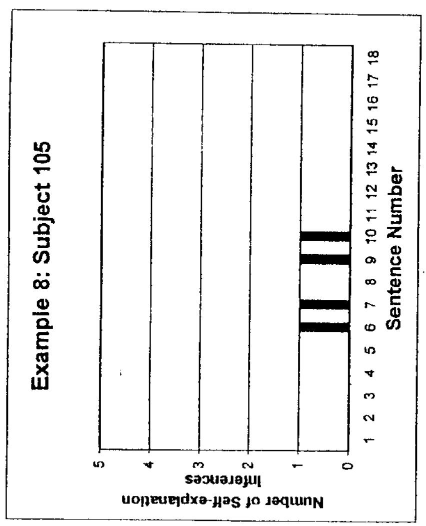

Example 5: Subject 105
Number of Self-explanation Inferences
Sentence Number

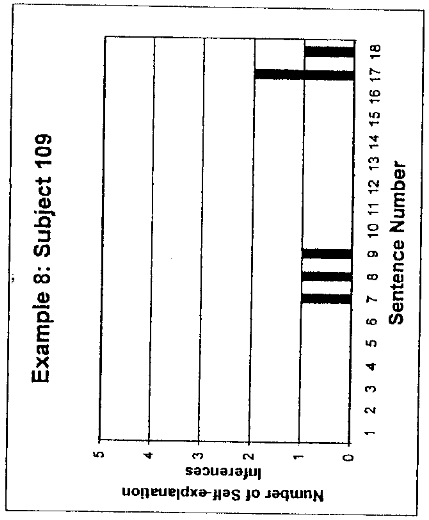

Example 5: Subject 109
Number of Self-explanation Inferences
Sentence Number

(c)

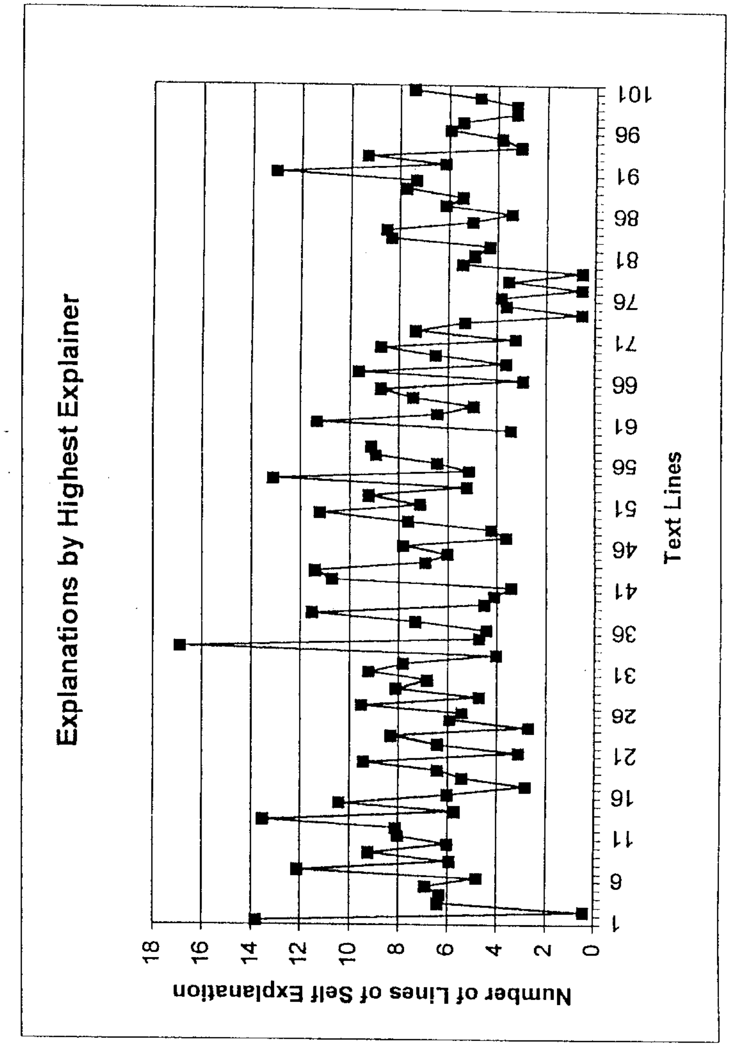

Example 8: Subject 103
Number of Self-explanation Inferences
Sentence Number


Example 8: Subject 107
Number of Self-explanation Inferences
Sentence Number

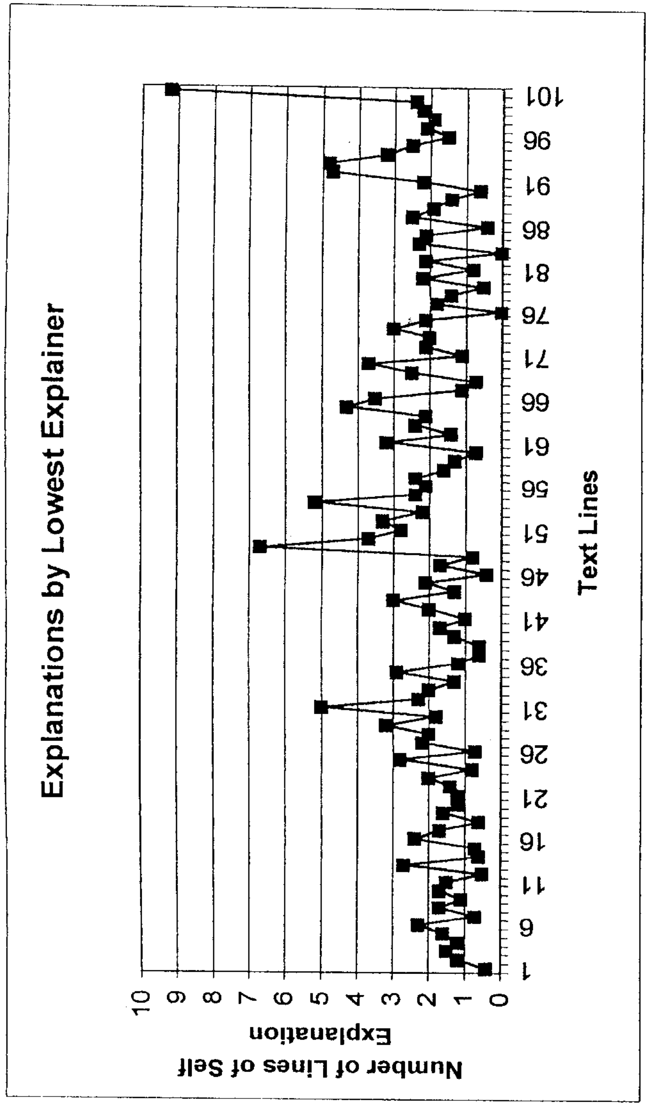

Example 8: Subject 105
Number of Self-explanation Inferences
Sentence Number


Example 8: Subject 109
Number of Self-explanation Inferences
Sentence Number

(d)


Explanations by Highest Explainer
Number of Lines of Self Explanation
Text Lines

(e)



(f)

FIG. 4.2. Distribution of spontaneous self-explanations across the sentences of three worked-out examples for four high explainers for Example 5 (a) and Example 8 (b), four low explainers (c, d), and for the best and the worst learner's enforced self-explanations (e, f).

Second, the inference-generating view should also predict that when students do explicate an inference at the same location, the inferences should be semantically equivalent, presumably because a relevant piece of information is missing. However, this is simply not the case: See again SEs#1, #2, #3, and #4, which were generated by four different students at the same location in the text (after reading S17).

A third finding that questions the inference-generating view is that unlike elaborations supplied by the researchers, self-explanations do not always make sense to the analyzers. They are often fragmented, and sometimes incorrect, whereas elaborations supplied by the researchers are always scientifically correct and meaningful. In fact, when a researcher supplies less meaningful elaborations (such as imprecise ones), then typically they are less helpful for recall (Stein & Bransford, 1979). In contrast, the fact that self-explanations are often either incorrect, fragmented, or meaningless to the coders, and yet still helpful to learning, raises the question of what purpose they serve. If these incorrect and fragmented SEs are viewed as incorrect inferences, then in principle, they should pose a problem for the learners in that they should hamper learning somehow. Yet, the fact that about 25% of SEs are erroneous, and yet students nevertheless learn from generating them, suggests that these may not be considered *incorrect inferences* analogous to incorrect elaborations. Again, the fact that incorrect SEs are not damaging to learning suggests that they may serve another purpose.

Thus, not only were explanations not generated uniformly across all sentences, even though the text passage as a whole omitted numerous pieces of information (such as the omitted information about the function), but moreover, when they do explain at any given location, there was hardly any consensus in what each student said. This pattern of inconsistency in when an explanation inference is generated and what is explained at each line of text questions the assumption that self-explaining only serves the purpose of inferring new knowledge that is missing from the point of view of a normative text model. Instead, self-explaining seems to serve another purpose, a purpose that is tailored to the individual student himself or herself. These unexpected findings, along with the individual differences finding in the differential number of SEI students generate, converge on the conjecture that self-explaining may be more than a process of inferring missing knowledge to fill gaps. The notion to be proposed here presumes that a student comes to the learning situation with some kind of preliminary mental model that can be incomplete and incorrect in many ways (thus, perhaps explaining the source of the 25% incorrect self-explanations). In this alternative perspective, self-explaining can be conceived of also as processes of revising one's existing mental model of the learning materials. Such a perspective can explain why some students would generate more SEIs than others (because the amount of self-explaining depends on their need to revise their mental model, which then depends on the frequency with which they perceive conflicts between their mental models and the text model). Thus, a revision view requires that we reinterpret self-explanations in the context of the student's existing evolving knowledge (or mental model) about the sentences that he or she is reading, rather than interpret self-explanations in the context of the correct scientific knowledge (the normative model) that a text embodies. That is, self-explaining is a process that students engage in for the purpose of customizing inferences to their own need. Hence, the alternative view to be proposed here is that self-explaining also serves the purpose of revision so that the processes of self-explaining allow the individual student to repair his or her own representation.

Undertaking Revision: The Imperfect Mental Model View

The unexpected findings cited in the previous section make more sense in the context of an imperfect mental model view. Such a view assumes that self-explaining is the process of revising (and updating[2]) one's own mental model, which is imperfect in some ways. Therefore, it makes sense that the majority of the students would not generate a semantically similar explanation at any given sentence location because each student may hold a naive model that may be unique in some ways, so that each student is really customizing his or her self-explanations to his or her own mental model. Similarly, it also now makes sense that there would be no consensus in when an explanation would be generated because presumably one would repair one's mental model only when a conflict is perceived. This revision interpretation also accounts for individual differences in the amount of SEs students generate: Presumably, they generate a SE when they perceive a conflict between their mental model and the text model (what the text describes). Hence, although there is no empirical support up to this point to

[2]It may be wise to refrain from using the term *updating* because it is used in the comprehension literature in a slightly different way than repairing or revising, as used here. *Updating* has been used in the sense of foregrounding or highlighting a specific part of one's mental model. Thus, updating corresponds to "the current status of objects or events described by the text" (McNamara, Miller, & Bransford, 1991, p. 496). There is no reference in the updating literature to any conflicts between the existing mental model and the text sentences.

unambiguously assert that mental model revision is one of the processes of self-explaining, the imperfect mental model framework at least accounts for all these heretofore unexplained findings coherently.

The *imperfect mental model view* assumes that students come to a learning situation with different imperfect preexisting mental models or build imperfect ones in the course of learning. It also requires that one develops a method to assess what the status of a student's initial mental model is prior to learning, which is a much more complex task than a text analysis. Fortunately, a method for capturing a student's mental model has already been developed and discussed in Chi, de Leeuw, et al. (1994) and is briefly redescribed in Appendix A. Such an assessment method reveals that students have preexisting mental models, and the majority of them are flawed. For the domain of the human circulatory system, we now know that students' initial mental models fall into six types, as shown in Fig. A.3, with 50% of the initial models being of the single loop type (more details later).

How to Operationalize Mental Model Gaps and Conflicts (or Violations)

To claim that self-explaining is a process of revision requires that we make assumptions about when revisions are required. In order to specify when the process of repair is needed, three issues need to be clarified: how mental models can be imperfect, in what ways do imperfect mental models correspond to or conflict with incomplete text models, and what is the implication of a correspondence or a conflict for the learning processes.

First, a mental model can be imperfect by having gaps of missing knowledge. Such gaps may or may not correspond directly to omissions in the text. (The term *omissions* is used primarily to refer to information missing from a text passage; however, these omissions do not destroy text coherence. The term *gaps* is used to refer to knowledge missing from one's mental model.) When gaps correspond to omissions, no conflicts between the mental model and the text model exist. The tacit assumption of the earlier work (Chi, de Leeuw, et al., 1994) was that gaps correspond to omissions. In order to account for the prompted or enforced self-explanation effect, we need to make an additional assumption that students are not often aware of omissions (except perhaps for explanatorily glaring ones, i.e., the crucial pieces of information) and/or gaps in their knowledge, unless they are explicitly told to reflect on their understanding. These two assumptions (that gaps correspond to omissions and students are not aware of gaps and omissions) explain why instruction to self-explain is beneficial. That is, one way to interpret the enforced self-explanation effect is that students are basically encouraged, through prompting, to induce the omitted information and gaps of knowledge.

Notice that the issue of whether or not mental model gaps correspond to text omissions, is tangential to the issue of whether or not a mental model is fragmented. Fragmented mental models may be defined to be ones that are missing connections. In much of the text comprehension research, it is often assumed that the goal of a constructive strategy is to make the representation more coherent by connecting ideas in the text (Graesser, Singer, & Trabasso, 1994). One could conceive of making connections as generating inferences that integrate knowledge. In this sense, the concern in the comprehension literature of making a representation more coherent is analogous to the benefit of self-explaining when gaps correspond to omissions.

Gaps, on the other hand, need not correspond to omissions in the text. In this case, the text explicitly spells out the information missing from a mental model. This means that sentences containing information that fill gaps of missing knowledge can simply be assimilated without much self-explaining. For example, a sentence (such as S22) that states <u>In each side of the heart blood flows from the atrium to the ventricles</u>, may simply be encoded directly without much self-explaining because such a sentence may simply fill a gap of missing knowledge. Consequently, when gaps can be filled by text information, the lack of correspondence between gaps and omissions does not cause any conflicts.

Before exploring circumstances under which conflicts do occur, we should first discuss what is not a conflict between a mental model and a text model. (Henceforth, the term *conflict* is used in its generic sense, and the term *violation* is used to refer to the specific type of conflict discussed here.) In the entire discussion in this chapter, various types of conflicts always refer to a discrepancy between the mental model and a text sentence or model, and not to conflicts between two text sentences, as in Glenberg, Wilkinson, and Epstein (1982) or Markman (1977). A violation cannot be merely a contradiction. A *contradiction* occurs when a sentence conveys some information that the mental model already has represented, but incorrectly. Suppose a student thought the size of the heart is about 10 inches in diameter and the text sentence says it is 7 inches, then this would constitute a contradiction, not necessarily a violation. A contradiction can usually be corrected without much self-explaining, and the more often a piece of incorrect knowledge is contradicted, the more likely it will be corrected (de

Leeuw, 1993). So, the issue boils down to how do we determine whether a text sentence violates a piece of knowledge or merely contradicts it. One way to discriminate between violations and contradictions is to assess the embeddedness of a piece of knowledge. A piece of knowledge (i.e., a belief) should be held with greater perseverance if it is highly embedded in a network of beliefs with multiple consequent nodes following that belief (de Leeuw, 1993).

A violation is also not a disagreement between two coherent views. That is, one can recognize that one holds a particular view that conflicts with a text view or a partner's view, without necessarily feeling the need to revise one's view. In this case, a disagreement is between two opposing views that are already learned and held in place.

Finally, a violation is not an anomaly. For example, in many physics experiments, students can clearly see that their predictions (e.g., of where the ball will land after being dropped by a moving airplane) are discrepant with reality (e.g., where the ball actually landed). Such a discrepancy between the ball's actual and predicted landing location may create a recognition that something is wrong, but the students generally have no idea what is wrong with their mental model as to produce an incorrect prediction. That is, the students have no idea what aspects of the correct text model violate their mental models; consequently, anomalies are often rejected or explained away.

To define a violation requires a second way of conceiving of imperfect mental models. That is, conceiving of imperfect mental models as ones having gaps assumes that the mental model is correct globally, with incorrect and/or missing knowledge at the local level. Alternatively, a mental model can be imperfect not only because it has gaps, but also in the sense that it is flawed. A *flawed mental model* can be defined as one that gives opposing or different predictions from the scientifically correct text model. A flawed mental model can nonetheless be consistent and coherent, in the sense that it can make the same consistent prediction over time, and the model also has internal consistency. For example, in the single-loop model of the human circulatory system, lungs are merely conceived of as another organ to which blood has to be supplied. In such a flawed model, one would not predict that blood goes to the lungs to receive oxygen and get rid of carbon dioxide. Instead, in such a single-loop model, the heart is the source of oxygenation, the heart acts as a unitary component, and blood goes to the lungs (as it does to other parts of the body) strictly for the purpose of supplying lungs with blood. Such a flawed model is distinctly different from the scientifically correct double-loop model because the two models would make different predictions about the need for blood to go to the lungs.

In the context of a flawed mental model, a *violation* requires a recognition that a piece of knowledge is violated in some causal way, in the sense that this flawed belief has some implication for additional consequences, so that a repair is not merely the case of replacing an isolated incorrect belief with the correct one. In this chapter, a *violation* is defined as a conflict between a text sentence and a belief that is embedded in a flawed mental model. Thus, a text sentence (S18) that reads <u>The right side pumps blood to the lungs and the left side pumps blood to other parts of the body</u> should violate the single-loop model because such a model would not predict that blood needs to go to the lungs for oxygen. This means that a student can recognize that a text sentence violates his or her belief if he or she somehow takes the effort to propagate the conflict so that he or she recognizes the consequences of changing that belief. Such effort can be undertaken by self-explaining. Thus, it is possible that, without taking the effort to propagate a conflict, a given sentence that violates a student's belief may be conceived of only as a contradiction.

When violations occur, different learning processes occur, depending on whether a student acknowledges the violation, misinterprets it, or rejects it. The process of *repair* (similar to *accommodation?)* occurs only when the student recognizes and acknowledges that a violation exists. When it is misinterpreted, then the student can assimilate the conflicting information, usually incorrectly. Typically, students misinterpret a violation to be consistent with their models. For example, the student below misinterpreted S18 by self-explaining:

> SE#9: "The right side of your heart gives blood to your lungs, and the other side, the left side, gives blood to every other part of your body."

The use of the word *gives* in this student's explanation clearly conforms to the single- loop model in that she has misinterpreted the sentence to mean that blood goes to the lungs merely to supply lungs with blood, and not to get oxygen. Thus, although this sentence should have violated the student's mental model, no violation was perceived.

Sometimes a sentence that should violate a student's mental model may be misinterpreted as a contradiction or filling a gap. For the same S18 that stated the right side of the heart pumps blood to the lungs and the left side pumps blood to other parts of the body, another student, whose initial naive model is also the single loop without lungs, treated the information in that

sentence not as a violation of her model, but as contradiction of what she already knew. She explained, "I never knew that before. Um, I always thought they all do the same thing. Um, nothing else." This SE shows that the student treated the heart as a unitary component without specialized functions in different parts of it. Moreover, the student treated the information in the sentence not as a violation of her mental model in that blood should circulate to the lungs to pick up oxygen, but rather, she treated the information as conveying new knowledge about the heart as having decomposable compartments with different functions.

From the examples just presented, it is clear that once a student's initial naive mental model has been captured, one can, in principle, determine whether a given sentence would or would not violate that student's mental model. Even so, it is still not obvious that a student would necessarily interpret the sentence as such. What in principle should be a violation can be interpreted by the student as actually being compatible with his or her mental model, as shown earlier, but requiring merely direct assimilation or correction. Thus, although a serious violation existed, a student may not interpret it that way.

How to Characterize Mental Model Repair

Although a way of defining violations has been laid out, it is nevertheless problematic to determine when violations are detected by the students. That is, although a posthoc analysis can easily show that self-explanations are usually generated in order to resolve a discrepancy in understanding, it is difficult to determine accurately when violations are detected. Three complexities exist. First, in order to predict more accurately when a violation exists, the researcher has to track the changes in the mental model as it evolves while the student reads and learns from the text. Second, even if the researcher can accurately predict when a violation should exist in the context of an evolving mental model, a student may not notice it (as when a sentence is misinterpreted or parsed incorrectly). Finally, even if a violation is recognized at the time that it was introduced, it may not be resolved until much later when more sentences are read. This means that one cannot accurately predict when a violation is detected, thereby one cannot predict when self-explanations would be generated to resolve it.

Given all these difficulties in tracking when a violation occurs and is perceived, another way to support the claim that self-explanations are in part mental model repairs (in addition to inference generation) is to characterize

TABLE 4.3
Characteristics of Repair

1. Pauses and uncertainty statements such as ums at points of conflicts.
2. Monitoring statements of failure to understand.
3. Repetitions of the same self-explanations.
4. Effortful and lengthy self-explanations in contrast to short confirmatory ones.

the kinds of self-explanations that can be observed on occasions when a violation is detected as well as occasions when no violation is detected. Table 4.3 lists four characteristics that can be captured.

First and foremost, because repairs should be undertaken when violations are detected, the detection of violations can be characterized by a great deal of uncertainties such as *ums* and pauses. Second, there should be evidence of monitoring statements of failure to understand. Third, the concept of repair also means that revisions of the mental model sometimes need to be strengthened. Repetition in self-explanations may be taken to characterize strengthening of one's mental model, whereas it is difficult to make sense of the purpose of repetition in an inference generating framework. Finally, when violations are detected and repairs are undertaken, self-explanations should be lengthy and effortful. However, if the incoming new information is consistent with one's mental model so that no violations are detected (but only gaps), then presumably the new information can be assimilated readily or ignored, reflecting short confirmatory self-explanations. In the next section, an example illustrates SEs that have these characteristics suggesting that self-explaining may also be a process of repair.

Note that the proposal is not that each of the aforementioned characteristics absolutely differentiates a revision view from an inference view, but rather, that there will be a differentiation in the characteristic of a self-explanation, depending on whether a conflict is detected or not, at the time the self-explanation was articulated. There is no a priori reason on the other hand, to expect differential characteristics of self-explanations, such as long versus short ones or effortful versus confirmatory ones, viewed from an inference-generating perspective.

A Microgenetic Analysis of a Single Case From a Second Biology Study

When the text was used as a context for interpreting self-explanations, it was fairly straightforward for Chi, de Leeuw, et al. (1994) to claim that

self-explanations were inferences. To make such a claim, one only had to know what information the text already provides and thereby conclude what information is omitted from the text, such as the function of a component. To then claim that such missing knowledge is inferred, one simply had to verify in the coding that such knowledge is present in the self-explanations. Thus, the coding scheme was fairly straightforward. Notice that the coding scheme could only support or reject what researchers expected to find: That is, the coding scheme tested the hypothesis of an inference-generating view in the same way that conventional experimental methods test hypotheses. (See Chi, 1997b for a discussion of this kind of coding method.) Therefore, our original incomplete text view dictated our coding scheme: Each proposition was coded within a self-explanation (in the biology study), or each idea unit (in the physics study), independently of one another, but in the context of the information provided in the text sentences. What had not been done was to code each self-explanation in the context of the student's evolving mental model. Only then can one differentiate and discern whether self-explaining is a mechanism of generating inferences or making repairs. The following attempts such an analysis in a single case for the purpose of illustrating how revision can be conceived of differently from inferencing.

In order to reanalyze SEs in the context of a self-repair (versus an inference-generation) view, one needs a new set of SE data because the SE protocols of the previous biology study were contaminated in the following way. In that study (Chi, de Leeuw, et al., 1994), after the students' initial mental models were captured, the students were further required to answer a set of pretest questions. These questions often contained premises that conveyed new information, allowing the students to change their initial models in some way. This means that one could no longer be completely certain what initial mental models students had coming into the learning phase. Thus, in order to make sure that a stable initial mental model had been captured prior to the reading and learning phase of the study, a second set of SE data was collected. This second biology study was improved in a number of ways for the purpose of capturing students' mental models more accurately. First, the question–answering part of the pretest was deleted and only the definition of terms and drawing of the blood path tasks were kept. Second, in order to capture the mental models more accurately, it was necessary to probe more deeply while collecting the self-explanation data, so that one can understand more completely what the students were explaining. The original biology study forbade the experimenter to deliver additional probes because the original interest focused on the effect of prompting for self-explanations. Consequently, in this study, if a student self-explained something that was not clear to the experimenter, the experimenter would then probe the student for further clarification. Under no circumstances, however, was the experimenter supposed to lead the student in any way, or provide additional information, or scaffold the student. This study involved six eighth-grade students studying the same circulatory passage.

Flawed Mental Models. If self-explaining is the process of self-repair, and if self-repair occurs primarily when a mental model conflicts with a text model, then one needs to first establish that some naive models are flawed and thereby are distinctly different from the correct scientific model. The single-loop model (the most common naive mental model, discussed in Appendix A) appears to be flawed because it generates different predictions from the scientifically correct double-loop model. Figure 4.3 depicts an idealized portrayal of a single loop with no lungs model. In such a model, blood carrying oxygen flows to all parts of the body, either simultaneously or sequentially from one part of the body to another part, then returns to the heart. The implicit assumption is that the heart oxygenates the blood. Lungs play no obvious role in circulation, although all students know that oxygen, as inhaled in air, enters the

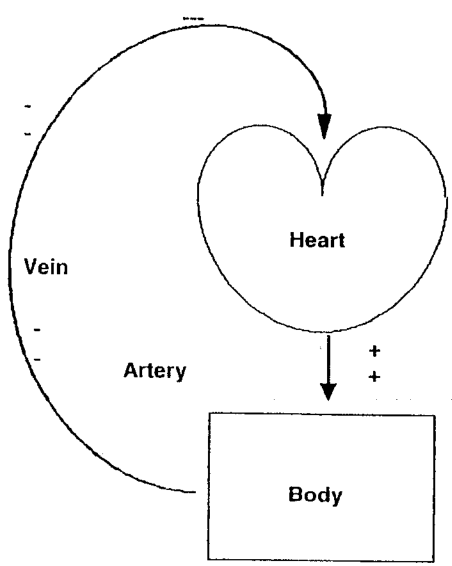


FIG. 4.3. Idealized single-loop model.

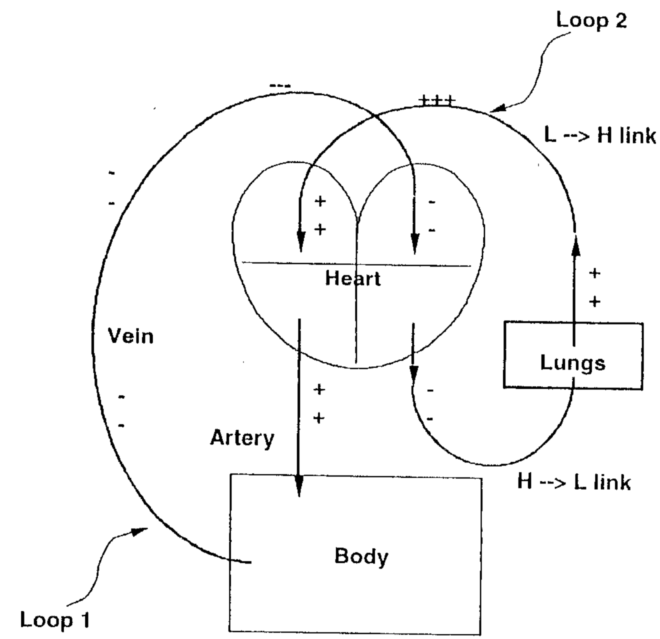


FIG. 4.4. Idealized double-loop model.

lungs. All parts of the body have been simply delineated as the body in the figure. Variations among students can occur in the details of the features, such as whether they know that the vessel leaving the heart is called the artery, whether they know that blood in the artery is oxygenated (depicted by the ++ signs), and so on. A single loop with no lungs also means that the student can talk about the lungs in the protocols, but the lungs do not serve a vital aspect of the circulation.

Three pieces of information about the double loop model (as shown in Fig. 4.4) violate the single- loop model (Fig. 4.3). These three pieces of conflicting information are that: the lungs are a component of the circulatory system, lungs are the site of oxygenation, and blood going to the lungs and returning to the heart constitutes a separate second loop in the circulatory system. The first piece of conflicting information—that lungs are an important component of the circulatory system—was first introduced in S18 of the text, and then again indirectly in S32 and S33. The second piece of conflicting information—that lungs are the site of oxygenation—was first introduced in S33. The last piece of conflicting information—that the heart–lung path and the lung–heart path constitute the second loop in the circulatory system—is partially presented in S34. In order to see whether self-explaining can be interpreted as a process of repair, the next section analyzes the characteristics of the SEs generated at these four loci of conflict (S18, S32, S33, and S34) in the context of a student's evolving mental model.

Four Self-Explanations at Points of Conflicts. In the abbreviated passage that was used to describe the circulatory system, only seven sentences have been presented prior to S18. These seven sentences primarily introduced the circulatory system, the heart, and its chambers. These seven sentences, as well as the sentences intervening between S18 and S32, are shown in Table 4.4.

It should be pointed out at this point that the student's protocols to be analyzed here were chosen randomly among the six students in this study. Each of the six students' protocols were not analyzed to pick the best one. Instead, a student who has an easily identified and robust naive model of a single loop with no lungs was chosen because that was the most common initial naive model among the 24 students of the 1994 study, for whom Chi, de Leeuw, et al. (1994) had captured their initial mental models (see Appendix A, Fig. A.3). It may be fortuitous, but the first student whose self-explanations were analyzed illustrated the concept of revision quite clearly.

In order to walk the reader through the processes of repair in the protocols, Fig. 4.5, the top row, depicts iconically what information is provided by the text sentences. The heading for each sentence also gives a sense of the critical information conveyed by that sentence. Thus, S18 conveys the idea that the lungs are a component of the circulatory system; S32 discusses the contraction of the right ventricle; S33 clarifies that the site of oxygen exchange is in the lungs; and S34 specifies the destination of the returning blood as being the left atrium.

The bottom row of Fig. 4.5 depicts what the student articulated in the self-explanations after reading each of the four sentences. Similarly, the heading of each SE summarizes the content of the SE. In SE18, the student misinterprets the information and conceives of the lungs merely as another destination; in SE32, this misconception is resolved and the student anticipates the lungs as the site of oxygen–carbon dioxide exchange; S33 reinforces the notion of the heart–lung link, and S34 summarizes the second loop. Although one assumes that the revision of a mental model is a cumulative process (i.e., that the entire mental model is retained in memory), the depiction does not carry forward what was constructed at each step of the

TABLE 4.4

Sentences Used in the Circulatory Passage

The Circulatory System:	
1)	Human life depends on the distribution of oxygen, hormones, and nutrients to cells in all parts of the body and on the removal of carbon dioxide and other wastes.
2)	These tasks are partially carried out by the circulatory system, which consists of the heart, an intricate network of blood vessels, and blood.
3)	The blood moving through the vessels serves as the transport medium for oxygen, nutrients, and other substances.
The Heart:	
4)	The heart is a muscular organ that pumps blood through the body.
7)	The typical adult heart beats 72 times and pumps about 5.5 liters of blood per minute.
Structure:	
13)	The heart consists of cardiac muscles, nervous tissue, and connective tissue.
17)	The septum divides the heart lengthwise into two sides.
18)	The right side pumps blood to the lungs, and the left side pumps blood to other parts of the body.
19)	Each side of the heart is divided into an upper and a lower chamber.
20)	Each upper chamber is called an atrium.
21)	Each lower chamber is called a ventricle.
22)	In each side of the heart, blood flows from the atrium to the ventricle.
23)	One-way valves separate these chambers and prevent blood from moving in the wrong direction.
24)	The atrioventricular (a-v) valves separate the atria from the ventricles.
25)	The a-v valve on the right side is the tricuspid valve, and the a-v valve on the left is the bicuspid valve.
26)	Blood also flows out of the ventricles.
27)	Two semilunar (s-l) valves separate the ventricles from the large vessels through which blood flows out of the heart.
28)	Each of the valves consists of flaps of tissue that open as blood is pumped out of the ventricle.
Circulation of the Heart:	
30)	Blood returning to the heart, which has a high concentration of carbon dioxide and a low concentration of oxygen, enters the right atrium.
31)	The atrium pumps it through the tricuspid valve, into the right ventricle.
32)	The muscles of the right ventricle contract and force the blood through the right semilunar valve and into vessels leading to the lungs.

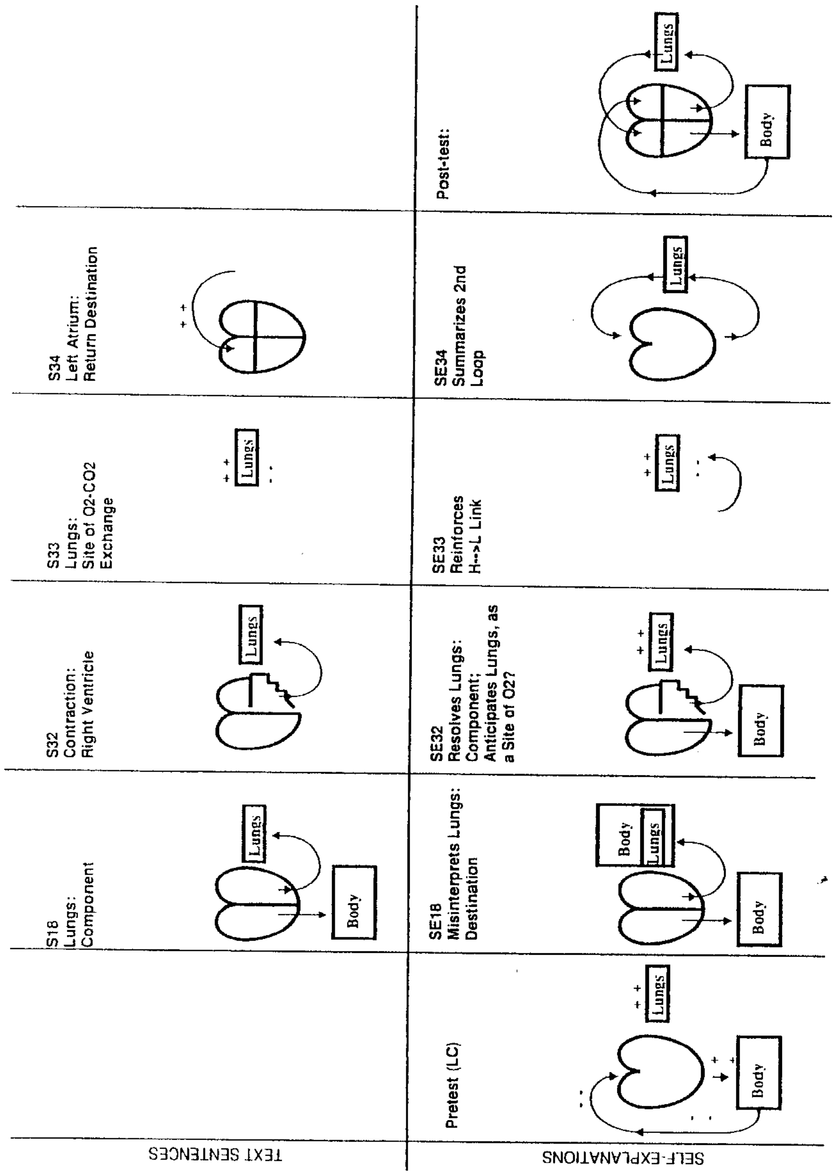


FIG. 4.5. Headings and iconic depictions of the content of S18, S32, S33, and S34 in the top row, with corresponding self-explanations generated by the students in the bottom row. The first and last columns depict the student's initial and final mental models.

TABLE 4.5

Self-Explanations of the Four Sentences

S18: The right side pumps blood to the lungs, and the left side pumps blood to the other parts of the body.

SE#18:

"Just that um, the right side is primarily for the lungs and the left side is to the rest of the body."

S32: The muscles of the right ventricle contract and force blood through the right semilunar valve and into vessels leading to the lungs.

SE#21:

(1) "(pause) Um, the sentence is a little confusing. It's like, it's almost wordy, sort of, I guess. Or something. Reading it once, I don't understand."

[Can you try to explain, you know, put it in better words? Or words you might use?]

(2) "(pause) I mean, I guess I understand now. I just, I can't think. I don't know, but kind of a muscle contraction that pushed the blood, um, through the valve and into vessels, but I don't know."

[Does the sentence make sense with your understanding of where blood is flowing in the circulatory system?]

"(pause) Mmm, yeah."

[So what is happening here, basically?]

(3) "Um, blood is just flowing from the ventricle into vessels and going, um, to the lungs, um, ok."

(4) "I guess, then I was remembering the thing about the left side is for the rest of the body, and the right side is mostly for the lungs, but well I guess I don't know."

[Well what, what are you thinking there?]

(5) "Well either, at first, I was just thinking that, you know, it was just providing the lungs with blood which didn't make much sense."

(6) "but that possibly, I don't know, but maybe it's going there [the lungs] to receive oxygen or something. I don't know."

S33: In the lungs, carbon dioxide leaves the circulating blood and oxygen enters it.

SE#33:

"OK, well then, so there, I guess so the blood goes to the lungs to um, get rid of carbon dioxide and have more oxygen put in it."

S34: The oxygenated blood returns to the left atrium of the heart.

SE#34:

"So, the blood leaves the heart, goes to the lungs, and comes back."

way in order to contrast more sharply what information was conveyed in the text sentence and what knowledge is explained in the SE. To be conservative, one assumed that what the student articulated is what is activated in memory. The first and last columns depict the initial and final mental models, based on the student's drawings and interpretation of its accompanying protocols in the pretest and posttest. The entire protocols of the four sentences and the self-explanations are shown in Table 4.5.

Now, one can read the SEs and see to what extent they characterize processes of repair. Note that the following analysis attempts to interpret the entire SE uttered after reading a sentence, in contrast to previous analyses: In the physics study, only the portion of each SE that contained physics-relevant comments were identified and coded; in the biology study, only SE inferences were coded.

The student's initial mental model captured from the pretest data of definition of terms is shown as a single loop in the first column of Fig. 4.5. The depiction is idealized in that she said blood went to the head, the toes, the hands, all of which are consolidated in the figure as *the body.* At pretest, this student did not know that the lungs were involved in the circulatory system (e.g., that oxygen is in the blood and that blood distributes oxygen), although she knew that lungs contain oxygen. (This is a common piece of knowledge among children of this age because they all know that the air people breathe in goes to the lungs, and we breathe in oxygen. Notice that the students mentioned lungs only because the instruction required them to discuss the role of lungs.) Therefore, the lungs have been depicted independently without them being linked to the circulatory system. This interpretation of her initial mental model on the basis of the definition of terms data is also consistent with her drawing of the circulatory system requested at the pretest. So, her model needs all three repairs, corresponding to the three potential violations that have been identified: She needs to add lungs to the circulatory path, she needs to attribute lungs with the function of injecting oxygen and extracting carbon dioxide, and she needs to add the pattern of blood flow to, and returning from, the lungs.

Her first chance to incorporate the lungs in the blood path is at S18, in which it mentions that the right side of the heart pumps blood to the lungs in the context of the location to which the left side pumps blood. Thus, the meaning of the purpose of lungs in this sentence is ambiguous, as shown:

> S18: <u>The right side pumps blood to the lungs, and the left side pumps blood to other parts of the body.</u>

This piece of information is referred to as the *heart-to-lung link* (depicted in the lower right-hand corner of Fig. 4.4 as the *H—>L link*); it is basically the first half of the other loop, where the blood path is directed toward the lungs. What she said at this point was:

> SE#18: "Just that um, the right side is primarily for the lungs and the left side is to the rest of the body."

At first glance, the fact that she confirmatorily rephrases that the right side is primarily for the lungs, seemed to have suggested that this piece of new information was easily assimilated, although it obviously violated her single-loop model. However, being able to read the subsequent self-explanations suggests that she misinterpreted this sentence to mean that lungs are just another destination to which blood has to be delivered, and for some reason, blood from the right side of the heart is reserved primarily for that specific destination—the lungs. Thus, the interpretation that is being offered at this point, is that she is thinking of the lungs not just yet as a component of the circulatory system, but merely as another destination to which blood has to travel. This interpretation is consistent with what she said during the pretest, when she described blood as going to the head, the toes, the fingers, and so on. Thus, naturally, lungs would simply be another destination for blood to go. (This interpretation is the same as the one given for SE#9, where the student talked about *giving* blood to the lungs). This interpretation, if correct, means that she had no conflict at this point because she viewed the text information as already consistent with her view, but with a slightly different emphasis. Thus, her explanation, at this point, is short and basically agreed with the sentence (Characteristic #4 of Table 4.3) and emphasized the fact that the right side is primarily for the lungs. It will become apparent that this interpretation is correct. This interpretation of her self-explanation is depicted in column 2 of Fig. 4.5, bottom row, whereby the lungs are embedded in the body, as if lungs are just a component of the body.

The next occasion at which she encounters the possibility that lungs play a role in the circulatory system is S32, in which the information in S32 reinforces the notion that blood circulates to the lungs, except it is presented as background information, as

> S32: <u>*The muscles of the right ventricle contract and force blood through the right semilunar valve and into vessels leading to the lungs.*</u>

Her self-explanation (SE#32), at this point, is long, uncertain, effortful, and contains six episodes. First, she monitors her confusion (although this sentence should not be any more confusing than other sentences):

> (1) "(pause) Um, the sentence is a little confusing. It's like, it's almost wordy, sort of, I guess. Or something. Reading it once, I don't understand."

After this confusion, the experimenter prompted the student with (experimenter's prompt is contained in square brackets and occurs only when the student seems confused and inarticulate):

[Can you try to explain, you know, put it in better words? Or words you might use?]

The second episode of her SE#32 focuses on acknowledging (by paraphrasing) the new, foregrounded information in the sentence about muscles contracting (up to this point, the heart has only been referred to as pumping, never as a muscle contracting), so she said:

(2) "(pause) I mean, I guess I understand now. I just, I can't think. I don't know, but kind of a muscle contraction that pushed the blood, um, through the valve and into vessels, but I don't know."

After this episode of uncertainty, the experimenter again prompted with:

[Does the sentence make sense with your understanding of where blood is flowing in the circulatory system?]

"(Pause) Mmm, yeah."

[So what is happening here, basically?]

After which the student summarized with:

(3) "Um, blood is just flowing from the ventricle into vessels and *going, um, to the lungs*, um, ok."

Notice that her summary is about the destination of blood flow, which is not the gist of S32 at all. Her summary excludes the details and inferences about contraction, the force that pushes blood, and the route of flow through the right semilunar valve. Instead, she mentioned the background information of going to the lungs. I interpret this to mean that this aspect of her mental model was incorrect and had to be repaired.

The fourth episode is her next unprompted SE, which, in effect, resulted from her noticing that this sentence reminded her of S18:

(4) "I guess, then I was remembering the thing about the left side is for the rest of the body, and the *right side is mostly for the lungs*, but well I guess I don't know."

This fourth episode of SE32 confirms the original interpretation that she had misinterpreted S18, so she is now trying to resolve her misinterpretation of what S18 said about the lungs and whether she ought to have treated the lungs as just as another destination or body parts. The experimenter prompted again:

[Well what, what are you thinking there?]

The fifth episode is her revision of her previous incorrect view that the lungs was just another destination, so here she says:

(5) "Well either, at first, I was just thinking that, you know, it was just *providing the lungs with blood* which didn't make much sense."

So the interpretation of her SE back at S18 is now supported by her remark just presented. With this new insight (that it did not make sense that blood flowing to the lungs was just going there to supply lungs with blood, but rather, it is going there for another purpose), she predicts in the next episode that the lungs might be the site of oxygenation, but waivers, continues to acknowledge conflict, and finally anticipates that going to the lungs may serve a different purpose:

(6) "but that possibly, I don't know, but maybe it's *going there [the lungs] to receive oxygen* or something. I don't know."

Basically, what she has learned here, as opposed to S18, is that blood flows to the lungs for another reason besides delivering blood (and oxygen). It goes there to get oxygenated. So, at this point, her mental model has incorporated two of the key pieces of conflicting information: that lungs are a component and they are the site of oxygenation. The representation of her knowledge learned at the SE of S32 is shown in Fig. 4.5, column 3, bottom row.

There are numerous characteristics to notice about this long SE at S32. First, she was extremely uncertain about what was going on, claiming that the sentence was confusing and did not make sense, when in fact, the sentence itself was no more confusing than any other sentence. One evidence of her uncertainty was the number of times she said *I guess, I don't know, maybe, not make much sense.* There were a total of 14 of these uncertainty comments and at least 6 *ums*. Smith and Clark (1993) showed that *um* should be interpreted as a longer delay before answering a question, indicating that the subject is aware that he or she does not know the correct answer (but is still hedging for time). The only interpretation possible for her uncertainty is that it arose from a conflict between the information conveyed in the sentence and her erroneous mental model of attributing the lungs merely as a blood destination rather than as a site for the purpose of oxygenation. Hence, in this SE of S32, it is clear that a conflict has been detected. Thus, this entire SE exhibits uncertainty (Characteristic 1 of Table 4.3) when a violation is detected. If this sentence is confusing, as she claimed, the confusion arose from this violation and not from the information about muscle contraction and the right semilunar valve.

Second, although the foregrounded information in the sentence dealt with the ideas of contraction of the muscles and blood flowing through the semilunar valve, such knowledge was not as problematic for her because these details provided no violation of her existing mental model, so that they can be readily incorporated. This means that no prolonged self-repair process is needed, although there is a knowledge gap. So she acknowledged this new knowledge briefly (in Episode 2), but focused the remaining episodes on the backgrounded information that blood went to the lungs. Thus, here is an example that illustrates how gaps in a mental model can be readily filled without much fanfare, if no violations exist.

Third, in four of the six episodes in SE#32, she puzzled over the possibility that blood flows to the lungs. Moreover, she continued to mention this conflicting piece of knowledge (that blood goes to the lungs) four times (in Episodes 3, 4, 5, and 6; these have been italicized). The four repetitions of this conflicting but backgrounded information presented in the sentence do not make sense in the context of the view that self-explaining is a process of generating inferences to fill gaps of missing information, because the knowledge that was repeated was already explicitly stated in the text: It is difficult to reconcile why one would need to repeat a text statement four times. Yet, the repetition makes complete sense in the context of repairing one's mental model (Characteristic 3 of Table 4.3), which did not initially incorporate this piece of knowledge in the right way. Hence, repetition makes more sense as a process of making the repair and/or reinforcing one's repair than a process of inferencing.

In sum, the features to emphasize about SE#32, at this point, are that the student finally noticed a violation between her mental model and the text information. This detection created a conflict for which she tried to resolve, resulting in the long and tortuous explanation. Her SE here was exceedingly long (Characteristic 4 of Table 4.3), not because the experimenter probed her for additional clarification (she was probed additionally precisely because she exhibited confusion, as compared with her SEs after reading S18, S33, and S34), but because she had to resolve her conflict. This SE is particularly telling for contrasting it with an inference in that although the sentence was really about contraction and semilunar valve, her explanation focused on the backgrounded information about going to the lungs. (An inference-generating perspective would have predicted that she elaborated on the new information given in the text, and in this case, it would be the foregrounded information.) In fact, after her initial claim of not understanding, and the experimenter probed her, she did say explicitly that "I guess I

understand now" (in Episode 2), obviously because she was referring to understanding the new information about muscle contraction and the valve (which was referred to in Episode 2). However, the differential way that various pieces of information in this one sentence is handled confirms the interpretation that a violation was detected. Finally, although such agony makes complete sense in this context, one would not have predicted, on the basis of a text analysis, that this sentence would elicit such a long and uncertain self-explanation. That is, this sentence is not technically harder to understand than the other three sentences, nor could one claim that this sentence omitted any particularly relevant information than the other three sentences, so that there is no a priori reason to expect S32 to evoke such a reaction.

The fact that lungs are the site of oxygenation was not actually described until S33, which says:

> S33: <u>In the lungs, carbon dioxide leaves the circulating blood and oxygen enters it.</u>

Because this knowledge had already been anticipated by the student in her previous SE (Episode 6 of SE#32), her current SE merely confirmed this piece of information, which no longer provides a conflict:

> SE#33: "OK, well then, so there, I guess so the blood *goes to the lungs* to um, get rid of carbon dioxide and have more oxygen put in it."

Thus, when the information conveyed in a sentence not only does not violate one's mental model, but also confirms it, the student expresses this with a simple confirmatory statement, such as *so there*. The student also took another opportunity to reinforce the notion that blood goes to the lungs.

S34 provides explicit information about the other half of the second loop, namely, the lungs-to-heart link and the location of the returning blood:

> S34: <u>The oxygenated blood returns to the left atrium of the heart.</u>

At this point, the student's SE says:

> SE#34: "So, the blood leaves the heart, goes to the lungs, and comes back."

Again, notice the characteristic of this very important SE. First, the information provided in S34 that was new to her had to do with the completion of the second loop. However, because encoding this half of the second loop (the lungs–heart link) does not conflict with her model at this point, the assimilation could be done readily, so her self-explanation incorporated this lungs–heart link. Her SE, at this point, basically summarized the complete second loop, that blood goes to the lungs from the heart and returns to the heart, as if she is seeing this loop by her mind's eye in her mental model. It seemed independent of the detailed content of the information conveyed in this S34: She ignored the information about blood returning to the left atrium, nor did she differentiate whether it was oxygenated or deoxygenated blood. Instead, she articulated the most important aspect of what she has learned: the presence of a second loop.

Figure 4.6 summarizes this microgenetic analysis by showing the frequency of utterances of repair Characteristics 1, 2, and 3, in the self-explanations for the four sentences for which researchers have predicted that a conflict might be perceived. In reality, violation was recognized only at S32, so that there was an abundant evidence of repair, such as pauses, repetitions, and monitoring statements of failure to understand. What is revealing is that these characteristics of repair statements give rise to a pattern of differential long and short self-explanations, as were the cases shown in Fig. 4.2. Presumably, when violations are detected, long and arduous explanations would be manifested, whereas when new information is consistent with one's mental model, then it can be either assimilated (if gaps exist),

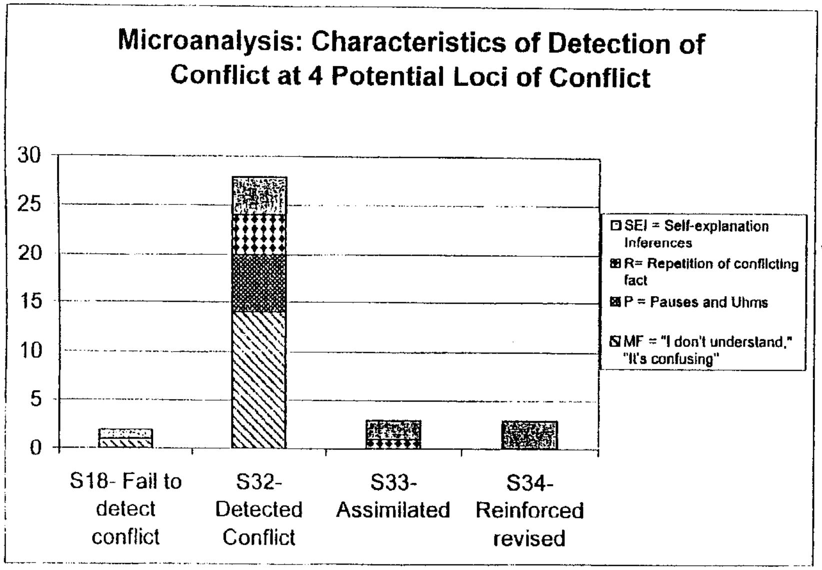


FIG. 4.6. Frequency of repair characteristics across four sentences.

agreed with (if it matches), or ignored, giving rise to a pattern of differential long and relatively short and confirmatory self-explanations.

Although only four characteristics of repair were specified a priori, the analysis itself revealed additional characteristics that could also be interpreted as consistent with a repair (and/or the successful detection of violations) interpretation. The most salient one is the focus on the backgrounded information rather than the foregrounded information.

It should be noted that this repair process, at the microscopic level, includes adding links and features that were not there originally (e.g., the relation between the heart and the lungs, that lungs are the site of oxygenation) integrating links such as the case of integrating the heart-to-lungs link with the lungs-to-heart link. Repair can also include deletion or removal of links and relation that have been seen in the evolution of other students' mental models. Thus, at a microscopic level, the repair processes per se are elementary operators such as addition, deletion, concatenation, or generalizing of features, operators that are well understood by cognitive scientists. At a macroscopic level, however, repair can be described as processes that are triggered by perceived violations and have the characteristics shown in Table 4.3. Thus, the original coding scheme of identifying self-explanations as individual pieces of knowledge inferences did not permit one to conclude that self-explaining included the process of mental model revision. It is only when the self-explanations, in the context of the student's evolving mental model are reinterpreted, could one then see that these self-explanations are not necessarily inferences that serve the purpose of filling gaps created by an incomplete text, but rather that some SEs, especially those at points of conflicts, are really manipulations that serve the goal of repairing an evolving understanding. This interpretation also suggests that the reference of self-explaining is the mental model, and not the external text.

Evidence Consistent With the Repair Interpretation

The interpretation that self-explaining is, in part, a process of repairing one's own mental model, rather than strictly a process of inferring missing information, was based on the analysis of a single subject's self-explanations in the context of her evolving mental model. This level of detailed analysis was necessary in order to portray the differences between a repair versus an inferring process. Analyses at this level of detail unfortunately also preclude the analysis of multiple subjects. However, the conclusion that the mechanism of self-explaining is also a repair process is consistent with other findings in the literature, as well as other findings that we could not previously explain. In this section, three sets of findings are cited that have been difficult to explain strictly in the context of an inference-generation interpretation, but make sense in the context of a repair interpretation.

First, if self-explaining is the process of inducing missing information, then presumably, if the researcher added this missing information, a text would be more comprehensible and one could learn from such a text better. For instance, students should be able to learn better from reading an elaborated versus an unelaborated text because the elaborations are generated on the basis of what the researchers think is optimal information that should be supplied. However, the results of this kind of study are not always consistent: Sometimes elaborations inserted into the text help and other times they do not (Recker & Pirolli, 1995; see discussion in Reder, Charney, & Morgan, 1986); whether they help or not depends on the readers' background knowledge (McNamara, Kintsch, et al., 1996). Therefore, it seems nearly impossible for an external agent (e.g., the researcher) to improve a text passage (by adding elaborations and inferences) so that a passage is uniformly comprehensible for all readers. Again, the lack of consistency in the benefit of inserting the missing information also suggests that one cannot think of self-explaining strictly as a mechanism of inferring knowledge to fill omissions in the text. The inconsistency can be understood in the context of a repair point of view. That is, the elaborations provided by a researcher, on the basis of a normative text analysis, may not always be the repairs that any given student needs in order to revise his or her own model.

Second, Webb (1989) found that generating explanations is generally more facilitative to learning than receiving explanations from others. Although this result is consistent with the constructive view in general, the result makes even more sense in the context of repair in that the students can repair their own mental models more effectively than have an external agent repair their models for them. That is, more generally, didactic instruction may be less effective than self-explanations precisely because such instruction is not tailored to repairing the individual student's mental model (Chi, 1996) largely because teachers and tutors cannot accurately diagnose what mental model students have (Chi et al., under review). Thus, explanations are most useful when they are generated by oneself because they serve the purpose of repairs.

Third, Chi, Bassok, et al.'s (1989) results on monitoring accuracy are consistent with the repair view. Conceiving of self-explaining as the process of self-repairing assumes that self-repairing is more likely to be undertaken if a conflict is detected by the learner. Monitoring statements sometimes reveal detection of conflicts. In the physics study, 39% of the protocols were coded as monitoring statements. These statements reflect self-assessment of understanding, such as "I can see now how they did it," or failure to understand, such as "Why is *mg sin theta* negative?" The results showed that the poor learners exhibited awareness of comprehension failure only 15% of the time, whereas the good learners acknowledged comprehension failures 46% of the time. This means that the poor learners thought they understood most of the time when, in fact, they did not, implying that they did not detect any conflicts between their understanding and what the text says. The relevant finding for the present discussion is that regardless of how frequently a student detects comprehension failures, once they detected them, it was generally (73% of the times) followed by episodes of self-explaining (Chi, Bassok, et al., 1989). Thus, when students realized that they did not understand, they must have perceived a conflict between their own mental model and the text information, and such conflicts elicited *self-explanation*, which is the process of trying to resolve the conflict. At the time, no explanation for this pattern was offered, that is, why detection of comprehension failures would lead to self-explaining. But with the self-repair view, one could say that self-repairing requires the successful detection of comprehension failure or some conflict between what the student thinks is going on and what the text is presenting.

If one assumes *monitoring* to be the process of comparing one's mental model with the text information, then the preceding interpretation suggests that the source of individual differences in self-explaining might be the frequency with which students monitor their understanding. In the physics data, if one computes the frequency of monitoring per sentence (rather than the amount of monitoring statements overall, as reported in the preceding paragraph), it is apparent that the high explainers monitored their comprehension more frequently (37% of the sentences) than did the low explainers (23% of the sentences). However, the frequency of monitoring does not necessarily imply that conflicts will be detected, although there is no question that the more often students monitor their comprehension, the more likely they are to notice conflicts (the correlation between monitoring understanding statements and monitoring misunderstanding is .79). This is because conflict detection may depend on a number of other factors, such as the status of one's mental model and correct interpretation or parsing of the text sentences.

In summary, although the proposal that self-explaining is, at times, a process of revision was based on analyzing the characteristics of a single student's self-explanations, these characteristics seem to fit a view of repairing an imperfect mental model, better than a view of inferring knowledge to fill gaps and omissions from an imperfect text. This view was proposed as a result of skepticism arising from some unexpected findings (e.g., no consistency in when and what self-explanations are articulated and the existence of individual differences in the number of self-explanations generated). Moreover, the repair view receives additional support when one projects certain characteristics requisite of self-repairing and not inferencing, such as the repetition of information that is already explicitly stated in the sentences (previous coding of self-explanations as inferences did not count these repetitions because these repetitions did not contain new information, and thus, were not coded as SEIs). These characteristics give rise to a distribution of differential (long and short) self-explanations. Additionally, in the process of analysis, other detailed differences also surfaced to support a repair view, such as focusing on the backgrounded rather than the foregrounded information. Moreover, the repair view seems to be consistent with evidence in the literature (e.g., such as no uniform benefit is derived from inserting inferences into a text, or that self-explaining is more effective than receiving explanations), as well as the analyses of the monitoring results. Thus, conceiving of self-explaining as a mechanism of repairing one's mental model, in addition to a mechanism of inferring information that is missing from a text, seems more accurate and complete. Finally, the self-repair view allows one to make sense of and tie in the monitoring results and postulate a potential explanation for individual differences in the amount of SEs that students generate. That is, if one conceives of *monitoring* as a process of comparison between the mental model and the external text, then it makes sense that a greater frequency of monitoring would lead to more opportunities to detect conflicts, which, in turn, would lead to self-repairs.

SUMMARY AND DISCUSSION

This final section begins with a summary of the mechanism that enables self-explaining to promote learning and shows how it can account for the most critical piece of finding, namely that there are individual differences in the number of SEs students produce, which then determine how well they learn. Several other related issues are also addressed.

The Process of Self-Repair

Originally, self-explaining had been portrayed as primarily the mechanism of inferencing, both inferencing from prior knowledge (either commonsense knowledge or domain-relevant knowledge), inferencing from integrating two or more pieces of information from the text, or inferencing by relating the new information in the text with prior knowledge. Moreover, the inferences supplied were seen as serving the purpose of inducing missing information that was omitted in the text sentences. However, the inference-generation view fails to explain individual differences in the amount of SEs generated, corresponding to the amount of learning gains observed. The presence of this individual differences finding, not accountable by ability or prior knowledge differences, poses a problem for understanding the kind of intervention that might be most effective to optimize learning gains. An additional mechanism for self-explaining is then proposed. Extended self-explaining is now conceived of as a process of repairing one's own representation, usually when a conflict is detected. Thus, individual differences arise from differences in the mental models students bring to the learning situation and/or the ones they construct. Moreover, even if two students have the same mental model at a global level, their mental models may have different gaps, and they may differentially notice whether or not text sentences violate their mental model. Finally, even if two students have exactly the same gaps, each of them may undertake different repairs, much as students do in repairing procedural bugs (VanLehn, 1982).

The proposal of a repair mechanism was first instantiated with a detailed analysis of a single student's self-explanations after reading four critical sentences (critical to changing the initially incorrect mental model the student had). Then, this interpretation was shown to be consistent with some of the findings in the literature at large, as well as some of our own findings that were heretofore unexplainable (e.g., the lack of consistency in terms of when and what SEs are generated). Most important, this repair view allows one to tie in the monitoring results and postulate an additional source of individual differences as differences in the frequency with which students monitor their comprehension.

What does one gain by viewing self-explaining as a process of repair in addition to a more straightforward process of inferring missing information? First, such a view explains the differential amounts of self-explaining students undertake, even when prompted. That is, it was always mysterious why some students explained and learned more (the high explainers) and others explained less, although both groups were prompted to explain and had similar ability and background knowledge. The explanation offered earlier—that the high explainers learned more because they explained more frequently or that they provided deeper explanations—was circular. The current view is that spontaneous and lengthy self-explaining occurs when conflicts are detected. However, whether or not conflicts are noticed in the first place depends on a number of other independent factors, such as the status of student's existing mental model and how a given sentence is interpreted in the context of it. For example, in the example presented earlier, S18 was misinterpreted by the student, thinking that lungs were just another body destination to which blood has to travel, therefore, the student did not perceive a conflict. Thus, various factors (other than ability and prior domain-relevant knowledge) can account for the differential accuracy with which students detect a conflict, thereby self-explain and learn. Because detection of conflicts generally encourages the process of resolution, prompted high explainers (in the biology study) may simply be those students who have accurately detected conflicts more frequently, and spontaneous high explainers (in the physics study) may simply be those students who monitored their comprehension more frequently and succeeded in detection.

Second, viewing self-explaining as a process of self-repair, requiring an accurate detection of conflicts, also suggests that prompting may achieve two additional benefits besides encouraging students to generate omissions. It may be a way of encouraging students to compare their own mental models with the incoming information (akin to the process of reflection; Collins, Brown, & Newman, 1989), thereby giving rise to more opportunities to notice conflicts. Prompting may also encourage students to propagate a contradiction (to see its consequences), causing a realization that the contradiction is really a violation. This suggests that prompting in fact promotes self-monitoring. Thus, this mental model revision perspective also illuminates the monitoring results.

What Happens With Incorrect Self-Explanations?

Self-explaining has been a nonintuitive learning activity because it was always assumed that a novice cannot learn without the guidance of an expert. That is, if a novice learner does not have the appropriate domain knowledge in the first place, what happens if his or her self-explanations are incorrect? It turns out that across Chi's studies, about 25% of self-explanations are incorrect. However, the basic pattern of results remains the same whether or

not these incorrect ones are included or excluded from the data analyses. Why are they harmless or do they, in fact, facilitate learning? One could not construct a sensible explanation of why incorrect SEs are harmless in the context of an inference-generating view only, but it makes complete sense in the context of a self-repair view. The harmlessness of incorrect SEs makes sense if one does not conceive of them always as inferences of omitted information. Such a conception should predict that they are harmful, analogous to the way supplying imprecise elaborations are harmful, as shown in the elaboration research (Stein & Bransford, 1979).

However, if self-explaining is conceived of at times as a process of repair, then one could even entertain the idea that generating incorrect self-explanations might actually promote rather than depress learning. That is, generating an incorrect piece of knowledge will more than likely create a conflict because the text is likely to refute it, either directly or indirectly (in Chi's data, about 26 out of 31 times, or 84% of the time, incorrect SEs are refuted by subsequent text sentences). Given that the detection of misunderstanding (as indicated by monitoring of comprehension failures) inevitably leads to self-explaining episodes (73% of the times, Chi, Bassok, et al., 1989), this would suggest that generating an incorrect piece of knowledge simply creates an opportunity for conflicts and misunderstanding to occur because the incorrect self-explanation will be challenged by the correct information from the text. Given that the detection of a misunderstanding then leads to self-explaining episodes of trying to resolve it (Chi, Bassok, et al., 1989), this suggests that generating incorrect self-explanations can actually promote learning.

If this hypothesis is correct, then one would predict that students would be more likely to learn a piece of knowledge if it conflicted with prior knowledge. In VanLehn's (in press) reanalysis of the (Chi, Bassok, et al., 1989) physics data, he found 11 target pieces of knowledge that students had to learn that were missing from the textbook. For each target, VanLehn judged whether the students had a belief that conflicted with the target. For 5 of the 11 targets, there were clear conflicting prior beliefs, and these 5 were significantly more likely to be learned than the 6 target rules without prior conflicting beliefs, suggesting that the presence of conflicts (with the possibility that they would be detected) does promote learning.

Comparison to Other Constructive Activities

Is self-explaining unique or different from other types of learning activities? In this section, six other constructive activities that students (instead of teachers) can engage in while learning from a source, such as a textbook (by reading), a lecture (by listening), or a model (by observing), are considered. These six activities are: self-questioning (or posing questions to oneself); explaining or posing questions to others; asking questions (for information that one does not know the answers to); answering questions posed by others; summarizing and notetaking; and drawing. All six learning activities have been explored in the literature and are shown to be effective at promoting learning to varying degrees.

The first activity, self-questioning or posing questions to oneself that one does not know the answers to also showed superior comprehension improvement when undertaken while listening to class lectures (King, 1991). In self-questioning, students are taught how to generate questions, usually using question stems such as "How is ... related to ... ?" or "Explain why ... " or "What do you think would happen if ... " Hence, one conjecture of why students learn from self-questioning is that in the process of trying to answer questions that they have generated using such question stems, they may experience feedback about what knowledge they fail to understand, and such feedback can alert them to the need of resolving their misunderstanding. This interpretation suggests that self-questioning is effective because it leads to some resolution of misunderstanding while the student is trying to answer the questions. Notice that self-questioning is very different from the kind of monitoring questions that students utter in the process of self-explaining, such as "Why is the knot the body?" (in reference to the knot versus the block in Fig. 4.1) or "Why does blood go to the lungs?" (in reference to the single-loop model in Fig. 4.3). These latter types of questions are much more content driven and do not fit neatly into question stems: They are really a form of query that points out conflicts between their mental models and the text's content model. However, one could say that self-questioning is effective because it is an initiating event that ultimately leads to the detection of misunderstanding in trying to answer it.

The second activity, explaining to others and posing questions to others seem different from self-explaining and self-questioning in that both self-explaining and self-questioning may be conceived of as an activity that manipulates and questions one's mental model, whereas explanations and questions posed to others may be based on information contained in the content of the text. Because explaining and posing questions to others is a constructive activity, it should promote learning gains to some degree. In fact, explaining to others is superior to receiving explanations, as Webb (1989) showed. It seems logical that the kind of questions students pose to others is derived from information in the text and not necessarily misunderstanding in their own mental models, although the latter possibility cannot be ruled out. There are no studies, to the author's knowledge, that contrast self-questioning or self-explaining with questioning and explaining to others. Explaining to others obviously can also result in mental model revisions.

The third activity, asking questions of others, presumably for information that one is lacking, can be a very effective learning strategy. Not only is it a constructive activity, but also, presumably, one asks questions about conflicts and misunderstanding in one's own representation. The opportunity to ask questions can be a reasonable explanation for the improved learning in a tutoring context as compared to a classroom context. According to Graesser's (1993) estimate, the opportunity students have to ask questions in the classroom setting is 0.11 questions per hour (including both deep and shallow questions), whereas the opportunity to ask questions goes up significantly in a one-to-one tutoring context, to 8 deep questions per hour. To the extent that the feedback provided to the students' questions are salient and appropriate, seeking these answers would help the students resolve conflicts and misunderstanding in their representations.

The fourth activity, answering questions, such as questions posed by a teacher or by a peer, is a constructive learning activity as well. To that extent, one would expect some learning gains. However, learning gains from answering questions are typically small (Hamilton, 1985; Redfield & Rousseau, 1981), unless the students are encouraged to generate more explanatory answers (King, 1990). The small gains in answering questions may result from the fact that answering questions obviously serves the purpose of others' goal, rather than the goal of revising one's own misunderstanding. Answering questions seems also less effective than asking questions (Davey & McBride, 1986).

The fifth activity is summarizing. A *summary* by definition, is like an abridged version of a text passage, which can be produced only after the students have read a longish passage. Summarizing seems to serve the purpose of the text rather than oneself because a summary, by definition, discourages the students from integrating the information in the external source, such as the text, with one's own knowledge. A summary that contains prior knowledge is usually considered to be inaccurate because it contains intrusions. Not surprisingly then, summarizing is less facilitating to retention of the lecture content after a 1-week delay than is self-questioning (King, 1992).

Although note taking can be a distinctly different activity from summarizing, it is similar to summarizing in that students often take notes by selecting key sentences from the text (as if they merely delete certain sentences from a text, much like the way students write summaries using the copy-and-delete strategy; Brown & Day, 1983). Again, being a constructive activity, one would predict that note taking would be an effective learning activity. It facilitates retention of text information after a 1-week delay, for instance, more so than rereading the text (Dyer, Riley, & Yekovich, 1979). Note taking is less effective, however, for retention of lecture content than self-questioning (King, 1992), which would be consistent with the self-repair prediction because self-questioning, like self-explaining, serves the learner's own goal.

The last type of activity, drawing, of either concept maps (Novak, 1993) or diagrams, are constructive activities that occur in a spatial medium. Drawing also seems to serve one's own purpose, so that the self-repair view would predict that it is an effective learning activity. However, drawing is limited in one peculiar way, but is superior in another way. The limitation is that one cannot make drawings to be as detailed and rich as one could in talking (such as self-questioning or self-explaining). Nor can drawing be done in as rapid a way as talking in self-explaining or self-questioning. The advantage of drawing is that one can look at one's drawing and make further inferences from it. For instance, drawing diagrams while solving geometry problems is particularly useful because further insights can be gained about relations depicted in the diagrams. Similarly, in a concept map, certain relations among nodes may be more transparent after a concept map is drawn. Because of the limitation of a spatial rather than a verbal medium, one would predict that it facilitates learning (as in the case of concept mapping; Novak, 1990), but the effect is sometimes small (Heinze-Fry & Novak, 1990).

The purpose of this exercise is to compare the relative effectiveness of each of these learning activities, in contrast to self-explaining. Although all these activities are constructive ones and promote learning to varying degrees, it is obvious that they embody different processes. Gross predictions were made about their relative effectiveness in terms of whether an activity involves self-repair or not. Clearly, such comparison statements can only paint broad strokes because the effectiveness of any given activity depends also on the quality of the product. For example, answering questions becomes a more effective activity when the students are asked to provide more elaborate answers (Woloshyn, Willoughby, Wood, & Pressley, 1990). Likewise, summaries may be more effective at enhancing learning if they were produced by condensation rules, such as invention and integration, rather than copy–delete rules (Brown & Day, 1983). However, it seems clear that the activities that are most facilitating to students are ones that serve the students' own goal of trying to understand in ways that allow them to question and repair their mental representations. In this sense, self-questioning might force the student to realize, in the process of trying to answer the questions, that they do not understand. Although self-questioning seems to differ from the kind of questions that usually occur when the student experiences conflicts (i.e., when there is a mismatch between the mental model and the content model), such as "Why is the knot the body?" or "Why is blood going to the lungs?" (perhaps these should be called *monitoring questions*), nevertheless posing questions to oneself can be a useful initiating event that can trigger self-explaining episodes.

What Type of Intervention Is Effective?

Assuming that students come into an instructional context (either in a classroom or in a one-on-one tutoring situation) with some preconceived notions of the content, they will thus have some existing mental representations that are incomplete and distinct from the scientific or correct conception. In such cases, a mental model repair view also dictates what types of intervention might be more appropriate. It suggests that it would not be productive to supply all the inferences missing from a text, and expect this type of manipulation to benefit all students, as confirmed by the studies of McNamara, Kintsch, et al. (1996), because these inferences may not necessarily correspond to gaps in students' mental representations. Rather, such a view suggests that the students themselves are in the best position to detect what gaps and conflicts exist so they may fix them, consistent with the commonsense view that didactic instruction is less effective than constructive learning. In fact, several pieces of evidence now suggest that it is difficult for an external agent, such as a teacher or a tutor, to know precisely what the students' existing mental representations are in that they cannot accurately diagnose what mental models students have and what conflicts they perceive (Chi, 1996; 1997c; Putnam, 1987). Consequently, the students themselves are in the best position to know what and how to modify and revise their representation, in light of the correct knowledge presented to them.

Assuming this interpretation is true, a more promising intervention might be a kind of prompting that encourages students to detect inconsistencies and violations between their mental models and the normative model, rather than focusing on the most optimal ways of conveying the correct information. A way to give them opportunities to detect conflicts is to ask them to reflect, self-question, or self-explain (i.e., prompting to self-explain may inadvertently also prompt them to reflect). This is consistent with Collins, Brown, and Newman's (1989) notion of reflection. *Reflective learning* is an activity of reflecting on one's choice of solution steps by observing one's own problem-solving steps or trace, and comparing them with the expert's trace. Thus, reflection is a comparison process, albeit discussed in the literature primarily in the context of a procedural task. Similarly, it might be equally useful to prompt students to reflect in a conceptual domain, whereby they compare their mental representations with the external information. Thus, a useful intervention might be some kind of prompt that can promote reflection.

Two Caveats

Two very important caveats need to be emphasized at the conclusion of this chapter. First, the self-repair view assumes that a student's naive mental model for a given domain and the scientific model are compatible, in that the naive model can be repaired in a cumulative way so that it can evolve eventually into the correct scientific model. It is under such circumstances that conflicts can lead to self-repairing, as it occurs through self-explaining. There are other domains and concepts, for which the students' initial mental models are completely incompatible, so that no amount of revisions can accumulate and lead ultimately to the correct scientific model, even if the students perceive conflicts. In such cases, instead of revision, the students should abandon[3] their initial mental models and initiate the construction of a new mental model. For example, if students initially conceived of natural selection as a causal event with a single or multiple causal agents, rather than an emergent event, resulting from the accumulation of multiple, independent, simultaneous, and uniform subevents, then no amount of revision of their initial model will result in the correct scientific model (Ferrari & Chi, 1998; Chi, in press). In such cases, it may be necessary to provide a metaframework (of an emergent event versus a causal event) for the student to construct interpretation of new information, rather than rely on the recognition of conflicts because conflicts, in this case, occur at the level of the metaframework. Preliminary data shows that providing such a metaframework facilitates understanding of domains for which the naive conceptions and the scientific conceptions are not compatible (Slotta & Chi, 1996).

A second important caveat is that the notion of conflict-driven learning leading to repair in a conceptual domain is reminiscent of the notion of failure-driven learning when expectations are violated (Schank, 1986) or impasse-driven learning leading to repair in a procedural domain (VanLehn, 1988). However, it is not yet clear whether conflicts, impasses, and failures are isomorphic. For example, *impasses* in a procedural domain are reached when a solver can no longer find any rules to apply to reach the goal, whereas *conflicts* are detected when sentences violate a mental model. The extent to which the mechanism of mental model revision corresponds to the mechanism of buggy-rule repair or gap-filling (VanLehn, in press) remains a deep issue that cannot be resolved in this chapter.

In conclusion, although there has never been any doubt that self-explaining is an effective constructive activity, the paradox has always been to explain how new and more complex cognitive concepts and procedures are constructed by the learner (Bereiter, 1985). Fodor (1980) stated this succinctly as:

> There literally isn't such a thing as the notion of learning a conceptual system richer than the one already has; we simply have no idea of what it would be like to get from a conceptually impoverished to a conceptually richer system by anything like a process of learning. (p. 149)

The mental model repair view presented in this chapter illustrates a case study in which one can see how a student can bootstrap her own understanding, and progress toward higher levels of accuracy in her mental model of the circulatory system, "without there already being some ladder or rope to climb on" (Bereiter, 1985, p. 205). However, in order to make progress, students need to recognize conflicts between their own mental models and the text model. In retrospect, if psychologists and educators had heeded Benjamin Franklin's wise remarks, they would not have bothered to study learning (as measured by remembering and forgetting) in the context of telling and teaching. Researchers should have known that they needed to focus on involvement, a form of which is self-explaining, in order to achieve learning. However, perhaps Franklin could have gone one step further, and added, "Challenge me and I understand."

[3]*Abandon* does not implicate forgetting or eliminating from one's memory. *Abandon* simply means that the student should not build on the initially retrieved mental model, but instead, construct a new mental model or build from another one.

APPENDIX A: WAYS OF CAPTURING AND VALIDATING STUDENTS' MENTAL MODELS

In Chi, de Leeuw, et al. (1994) a method was developed to capture one aspect of the representation of the circulatory system, namely, the representation of the blood-flow pattern (henceforth referred to as the *mental model*). In order to know what initial mental model of the circulatory system the students already have as they embark on the reading task, their initial mental models of the circulatory system were captured from the protocols collected from the tasks administered in the pretest. In the pretest, students were asked to define terms such as the *atrium*, the *heart*, *valves*, *veins*, and so forth (23 terms in all). They were also asked to draw the path of blood flow throughout the body, given an outline of the body with the requirement of including the heart, lungs, brain, feet, and hands in the path. A mental model of the connections of the components and the flow of blood can be pieced together on the basis of what they say. So, for instance, from the definition given for the term *artery:*

> Artery is a general term for all tubes that are from the heart and they carry the clean blood from the heart to all the body ... it [the body] always needs clean blood and the blood travels through the arteries and when it's used, it travels back up in the veins to go back to the heart, the heart cleans it again, ummm, replenishes it with oxygen, umm, and then it goes again to all the parts of the body.

One can tell, in combination with the explanations given while drawing the blood path, that this student had the preliminary model as shown in Fig. A.1. This preliminary assessment of the student's mental model then underwent continuous revision and updating as we integrated additional definitions, such as the one made for *heart:*

> The blood goes in at the upper right chamber and it then goes down to the downward right chamber, then it goes to the downward left chamber then it goes to the upward chamber then it goes out of the heart. And each chamber is divided by a valve that makes sure the blood goes in one direction.

These additional statements allowed more details to be added to the depiction of the student's model so that it now looks more enriched, as shown in Fig. A.2. After several iterations through all the protocols students generated from defining the 23 terms and drawing the blood path in the pretest, each student was credited with a composite initial mental model. Although a great deal of variations existed among the students' models, it was possi-

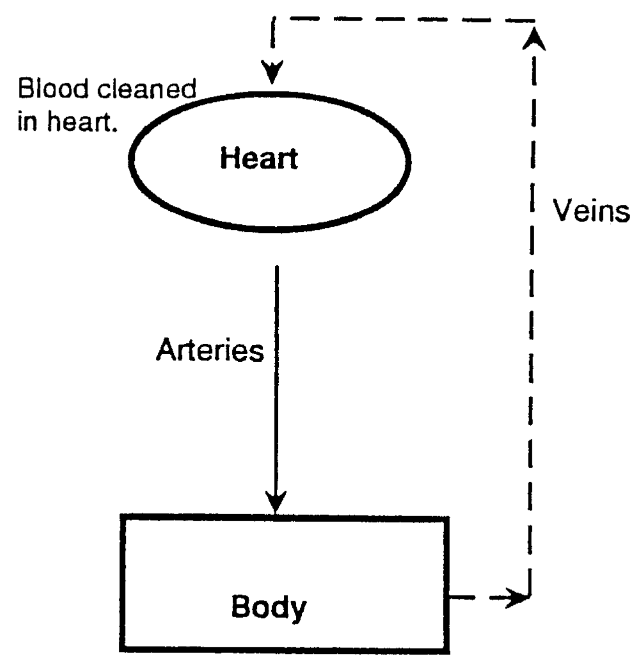


FIG. A.1. Capturing a student's mental model of a single loop (taken from Fig. 4.5, Chi et al., 1994).

ble to discern six general types, as shown in Fig. A.3. These six types ranged from the least accurate to the most accurate: no loop, ebb and flow, single loop, single loop with lungs, double loop-1, and double loop 2. The mental model depicted in Fig. A.1 is primarily a single-loop model. From the protocols of the 24 students in the Chi, de Leeuw, et al. (1994) study (10 from the control group and 14 from the prompted group), the majority of the students (12 out of 24) had the single-loop model as their initial model. Fig. A.3 also shows the number of students (out of 24) that had each type of models.

This initial identification of the student's mental model was further validated in the following four ways. First, the depiction of the blood path from Chi's analyses of the protocols should be consistent with the student's own sketch of the blood path. Figure A.4 shows what the student drew along with the following explanations:

> Um, it starts at the heart ... first it goes up to the brain, then. ... It goes back down to the arms, back up the arms, down to the feet, then back up ... to your heart

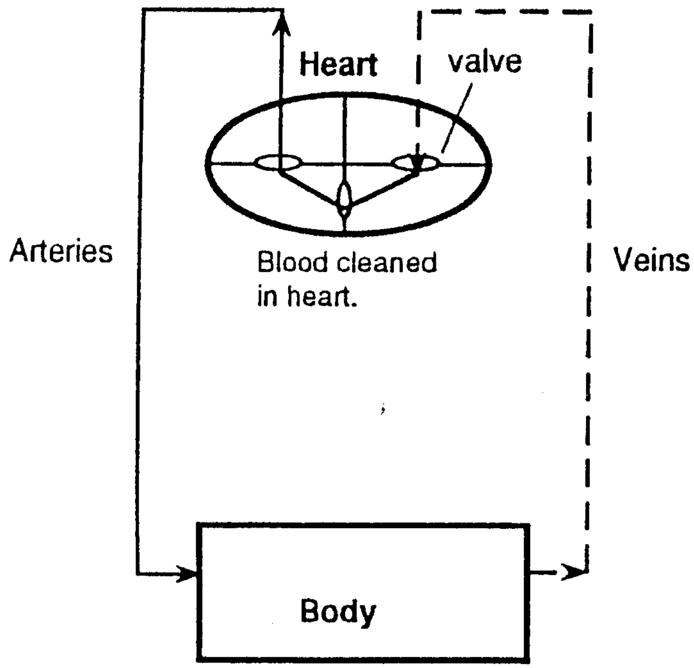


FIG. A.2. Capturing a student's evolving and enriched mental model (taken from Fig. 4.6, Chi et al., 1994).

> and then the process repeats itself. ... And I don't think the lungs have anything to do with where the blood goes. I think the lungs are just there because they're like right near the heart.

Basically, this is a single loop in that the blood is going to all parts of the body, then returns to the heart, where the student thinks blood gets replenished with oxygen. Thus, the heart is the site of oxygenation and it is not clear what role the student thinks the lungs play.

A second way to validate our analysis of the student's mental model was to predict, on the basis of the student's identified initial mental model, either which of the questions in the pretest they can answer correctly or how they would answer such questions. Thus, a subset of questions can be selected that is tailored to, and diagnostic of, each individual student's initial model. For example, a diagnostic pretest question for a single-loop model is the following: "Does blood change in any way as it passes through the heart?"

A student with a single-loop model would answer that the blood does change (in that it becomes oxygenated) because such an answer would be consistent with the incorrect assumption of the single-loop model that the heart is the site of oxygenation, as is shown in the following:

> Yes. It passes through the heart, um, the stuff that needs oxygen gets oxygen, and then it goes through the body, and then when it comes back, it needs oxygen again, and it gives it more oxygen. Then it leaves the heart again. So yes, it changes.

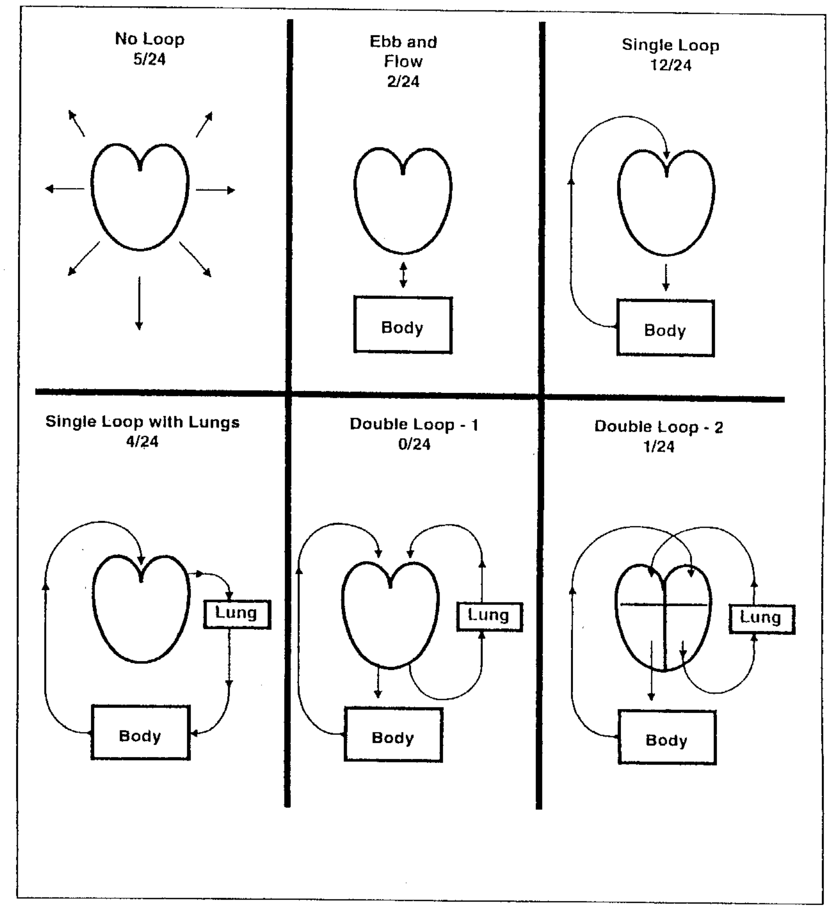


FIG. A.3. Six general types of student mental models and the proportion of students having each type.

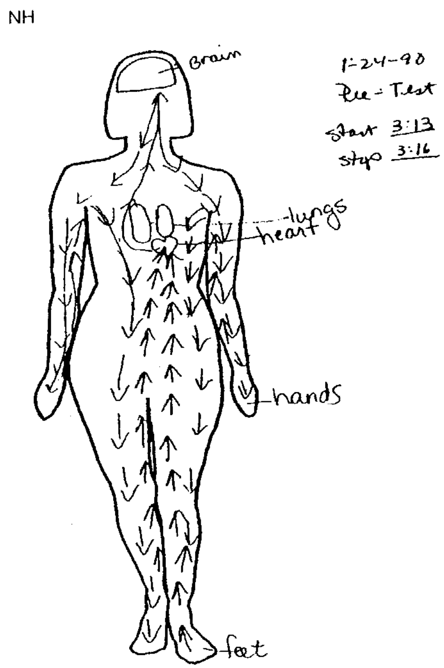


FIG. A.4. Blood path drawn by a student.

A third way to validate our analyses of students' mental models is to define a set of critical features for each of the six types of models. For example, some of the critical features of the single loop with lungs model are that the heart pumps blood to the lungs and that lungs play a role in the oxygenation of blood. Each student's protocols were then reread in order to ascertain that each of the critical features of the model with which the student was credited was indeed mentioned.

Finally, to further show that there is some validity and reliability in the way in which the students' mental model have been captured, Chi, de Leeuw, et al. (1994), have shown that their mental models improved substantially from the initial to the final state. All of the four high explainers

reached the most sophisticated double-loop-2 model at the posttest, whereas only one out of the four low explainers did. A similar contrast is obtained for the prompted versus the unprompted students. Eight out of the nine prompted students reached the double-loop-2 models, whereas only 2 of the 9 unprompted students did. Hence, the mental model analysis seems valid given that the models' improvement from pretest to posttest corresponded to the students' improvement in their answers to the posttest questions.

In summary, the four sets of measures serve as different forms of validation so that we were fairly confident that our method did capture the mental models with which we have attributed to the students.

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