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Self-Explanation: Enriching a Situation Model or Repairing a Domain Model?

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When people are reading a difficult text, one of the things they may do is talk themselves through the difficulty. That is, they might start explaining to themselves the parts they do understand, try to think of related knowledge that might help them understand the rest, and/or make an effort to problem-solve the gaps in their understanding. These efforts by readers to explain a text to themselves are what we call *self-explanation* (Chi & Bassok, 1989). Because self-explanation is directed toward a goal (understanding the text, or what the text describes), and requires conscious thought and effort, we think of it as an intentional strategy on the part of the reader. In this chapter, we consider the process of self-explanation in the context of two accounts of learning from a text, the Mental Model Revision view of Chi (2000) and the Construction–Integration model (Kintsch, 1998). Although there are some core similarities between these accounts of how readers combine old and new knowledge, they do yield some different predictions about intentional processes in general and self-explanation in particular. Some evidence that speaks to these differences is presented in the latter half of the chapter.

Many of the examples that follow are taken from deLeeuw (2000). In that study, 17 middle school students were instructed to self-explain after reading each paragraph of a textbook chapter on the human circulatory system (Towle, 1989). This choice of examples matches the focus in this chapter on directed self-explanation while reading a descriptive text.

WHAT IS SELF-EXPLANATION?

Self-explanation occurs whenever people explain a problem out loud as they solve it, or a text to themselves as they read it. It may occur spontaneously (e.g., Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Pirolli & Recker, 1994), or in response to instructions (e.g., Bielaczyc, Pirolli, & Brown, 1995; Chi, deLeeuw, Chiu, & LaVancher, 1994; Coleman, Brown, & Rivkin, 1997). There are ample demonstrations that instructing students to self-explain while problem solving results in better solutions (Chi et al., 1989; Didierjean & Cauzinille-Marmeche, 1997; Mwangi & Sweller, 1998), and that having them self-explain while reading results in better understanding of the text (Chi et al., 1994; Coleman et al., 1997). The processes involved in self-explaining while reading and while problem solving may or may not be very similar. This chapter concerns itself with self-explanation while reading in response to instructions.

The general instruction to explain what one is reading (Chi et al., 1994; Coleman et al., 1997) results in a larger class of utterances than those we call self-explanations. Following Chi (2000), we refer to self-explanations as those statements that are concerned with the topic of the text. This excludes self-monitoring statements ("I'm having trouble understanding this"), text-monitoring statements ("This is confusing"), and other non-topic-oriented statements ("I'm thirsty"). Self-explanations also include summaries and paraphrases that in some way restate knowledge that is already in the text, although these are not the focus of our work. The subclass of self-explanations that is of most interest is what Chi (2000) called *Self-Explaining Inferences*, or SEIs. These are on-topic statements that go beyond the information presented in the text. Self-explanations, then, are a subset (the topic-relevant ones) of what people produce when asked to vocalize while reading, and SEIs are the subset of self-explanations that are more than restatements of information in the text. They are analogous to elaborations and inferences of the information in the text. Chi et al. (1994) showed that among subjects instructed to self-explain, those who produce more SEIs show the greatest increase in understanding.

Self-Explanation in the Context of Mental Model Revision

The mental model revision view (Chi, 2000) starts with the assumption that learners have an existing mental model of what they are going to read about, before they start reading. Thus if they are reading a chapter about the human circulatory system, the assumption is that they know something about the heart and the blood, veins, and arteries, before they ever start reading. This mental model of the text domain is referred to as a *domain model*, to distinguish it from other varieties of mental models. In our work with the circulatory system, for example (Chi et al., 1994), we encountered students who believe that the heart oxygenates blood, or that red blood cells carry nutrients, to give just a couple of examples. We also found students who could not describe how the lungs fit into the system, or who could not distinguish between veins and arteries. The domain model is therefore thought of as a mix of correct and incorrect knowledge, which may have large or small gaps of knowledge relative to a more expert description, such as that presented in a textbook.

The mental model revision view further assumes that not only do students often come into a learning situation with an existing, often incorrect domain model, but that their preexisting domain model is flawed in a coherent way (Chi & Roscoe, in press). By coherence we mean both that the flawed model is an internally consistent one, and that it embodies an identifiable set of alternative or incorrect assumptions. The coherence of a domain model can be assessed either empirically or analytically. Empirically, coherence in the internally consistent sense means that students can use their domain model to give predictable and systematic answers to questions, and do so consistently. For example, about half of the eighth-grade students tested in the Chi et al. (1994) study thought that the human circulatory system was organized as a "single loop," in which blood goes from the heart to the body and returns to the heart for oxygenation. On the basis of such a flawed model, one can predict that their answers to the question "Why does blood have to go to the heart?" would be "To get oxygen." The second sense of coherence, that models embody an identifiable set of alternative assumptions, can be determined analytically through an analysis of the domain. For the domain of the human circulatory system, we identified three fundamental assumptions that differentiate one of the flawed mental models, the "single loop" model, from the correct "double loop" model. For example, the single loop model differs from the correct double loop model in systematic ways, in their assumptions about the source of oxygen, the purpose of blood flowing to the lungs, and the number of loops. That is, all students with the single loop model assume that it is the heart (rather than the lungs) that provides oxygen; that blood goes to the lungs to deliver oxygen (rather than to exchange carbon dioxide and oxygen); and that there is just one loop rather than two (Chi & Roscoe, in press), even though there are variations among the single loop models that students hold.

In the mental model revision view, learning from a text is a process of repairing the existing domain model. This involves three kinds of processes: (a) insertions of information from the text into the domain model; (b) replacement of wrong knowledge in the domain model with correct information from the text; and (c) inferences of new knowledge that is not explicit in the text, but that specifically addresses flaws in the domain model. An example of a straight insertion would be the student who knows that arteries take blood away from the heart and that veins take blood to the heart, but does not know anything about the function of capillaries. That student could insert information about the role of capillaries, which is to take blood from the arteries to the veins, without any further revisions to his or her domain model. An example of replacement would be the student who believes that veins take blood away from the heart, but learns that arteries perform that function instead. The role of inferences is seen as especially important in tailoring what is learned from the text to the reader's existing domain model. For example, few texts, including the one we studied (Towle, 1989) specifically state that the heart does not oxygenate blood. They state what the heart and lungs do, but the reader who believes that the heart oxygenates blood must infer that this is wrong, thus making a crucial correction to their domain model.

In this context, self-explanation inferences are an observable manifestation of the process of repairing a flawed but coherent domain model. Readers reveal in these statements how it is that they resolve the differences between their domain model and the text, in order to produce a new and better domain model. For example, Chi (2000) analyzed a single subject's protocols in the context of the subject's existing flawed single loop domain model. Many of the explanations were meaningless unless they were interpreted from the perspective of attempts at repairing the student's flawed mental model. That is, the explanations this student produced were shown to be specifically directed toward the flaws in her domain model, and created a resolution of the conflict between her single loop domain model coming in, and the double loop described in the text. Thus, self-explanations appear to be overt manifestations of the processes of repairing one's existing flawed domain model.

Self-Explanation in the Context of Situation Model Building

Although the mental model revision approaches focus on how new knowledge can change the understanding of a domain, they do not attempt to explain how new knowledge is acquired from a text. This is the focus of comprehension models, including the construction–integration (CI) model (Kintsch, 1998; Kintsch & van Dijk, 1989). Self-explaining inferences can also be viewed as fitting into this framework. This framework provides an alternative hypothesis about the function of SEIs: instead of being called on in the service of repairs to an existing mental model, they may be called on to aid in the creation of a new mental model that is a representation of the text. In the next section, we briefly lay out a basic outline of this model, and then explain how SEIs can be seen in this context.

Comprehension Processes to Build a Situation Model. Comprehension processes in the CI model consist of building basically two levels of representation: a propositional text-based representation and a situation model (van Dijk & Kintsch, 1983). Because deep comprehension in the context of learning a scientific text is affected mostly by the quality of the situation model (Kintsch, 1986, 1994), we focus on the construction of the situation model in the CI model and its contrast to the repair of a domain model in self-explaining.

The basic assumption of the CI model is that comprehension is the building of an episodic representation of the situation described by the text. This episodic representation is referred to as the situation model, analogous to a mental model of the situation described by the text. The situation model is an integrated network that combines a propositional text-based representation (reflecting the microstructure and the macrostructure of the text) and prior background knowledge. However, because prior knowledge is activated on the basis of the nodes and links in a text-based representation, it seems that the situation model must be determined, to a large extent, by the text-based representation. That is, the situation model is an *enriched* and elaborated version of the text-based representation.

For example, suppose a student is reading the sentences: "When a baby has a septal defect, the blood cannot get rid of enough carbon dioxide through the lungs. Therefore, it looks purple." A text-based representation is built, consisting of a proposition network linking the nodes (baby; septic defect; blood; carbon dioxide; through the lungs) by relations (baby *has* a septal defect; blood *cannot get rid of* carbon dioxide), and relations among the linked nodes (baby has a septal defect *when* blood cannot get rid of carbon dioxide). The text-based representation consists of meanings with direct links to the words in the text. It encompasses the literal representation of the text, without elaboration or intrusions of knowledge. Assuming that there are no coherence omissions in the text, such as missing referents and argument overlap, all students are capable of constructing pretty much the same text-based representation of these two sentences. (Note that *coherence* is used here to refer to the text, not the mental model.)

However, in order to understand these two sentences, background knowledge about the circulatory system must be retrieved and incorporated into the network. For example, one might need to relate knowledge about the septum, that it usually separates the red blood (carrying oxygen) from the purple blood (carrying carbon dioxide), to the "septal" node in the text-based representation. Likewise, the node "through the lungs" will activate relevant knowledge such as "Blood gets rid of carbon dioxide through the lungs." Notice that the relevant knowledge that is retrieved and becomes integrated with the text-based representation is driven by local associations and activations (Kintsch, 1998), such as the association of "through the lungs" with the activated knowledge about "blood getting rid of carbon dioxide through the lungs." Aside from the details of how the CI model works (i.e., once all the relevant associations are formed, then spreading activation processes select those portions of the activated knowledge that are strongly interconnected and inhibit isolated elements), the resulting effect is that only contextually appropriate knowledge remains. Thus, the situation model consists of the correct text knowledge integrated with the relevant retrieved prior knowledge.

When Automatic Comprehension Processes Fail. As long as the largely automatic processes involved in construction and integration are successful at building a coherent situation model, there is no reason for readers to engage in anything as effortful as explaining the text to themselves. But readers sometimes get stuck, particularly when there are problems in the text itself. We divide problems in the text into two general kinds that we call *text-structure omissions and text-content omissions.* Either may result in the use of additional processes directed at resolving some incoherence in the emerging representation of the text.

Text-structure omissions are problems in the text that lead to difficulty in establishing a coherent text base. These may reflect, for instance, a failure of the text to sufficiently signal how the proposition related by a given sentence is connected to the propositions from previous sentences. Such connections are normally established by overlapping arguments and explicit connectives. For example the following two sentences from Towle (1989) are connected by argument overlap:

Each side of the heart is divided into an upper and lower chamber.

Each upper chamber is called an atrium (AY-tree-uhm), and each lower chamber is called a ventricle (VEN-trih-kul).

The upper and lower chambers are each explicitly referred to in each sentence. The following two adjacent sentences, on the other hand, are not explicitly connected:

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

One-way valves separate these chambers and prevent blood from moving in the wrong direction.

It is up to the reader to make a connection and realize that *these chambers* refer to the *atrium* and the *ventricle.* The reader may supply these connections on the basis of propositions from earlier sentences, or from background knowledge, or by inference. In the majority of cases, these types of inferences are effortless and are considered automatic. One type of these automatic inferences are bridging inferences, such as substituting the referent for a pronoun ("the heart" for "it"). The second variety of automatic inferences, automatic generation, is similarly "effortless." For example, connections may be induced based on overlapping arguments to propositions. A subject who reads that "Deoxygenated blood flows through capillaries that merge and form larger vessels called venules" (Towle, 1989) may automatically generate the unstated proposition that deoxygenated blood flows through venules. These automatic processes are not considered true inferences by Kintsch (1998) because they occur as a natural consequence of the construction and integration processes. Nor are they candidates for SEIs according to Chi (2000), again because they are automatic. Only occasionally, though, the reader may not supply a connection at all.

Text-structure omissions can cause difficulty in comprehension. For example, the potential difficulty that these omissions create has been demonstrated in studies that present alternate versions of the same text to different subjects. Britton, Van Dusen, Glynn, and Hemphill (1990) compared recall for four different versions of two texts about the Korean and Vietnam wars. A computer simulation of the Kintsch theory (1984) was used to determine which texts required more inferences to repair problems in argument overlap. The recall scores for these passages were negatively correlated with the number of inferences required, so the more coherent texts were more memorable. A similar finding comes from Britton and Gulgoz's (1991) study, which created a "principled" revision of a text about the Vietnam War, with principles derived from the Kintsch and van Dijk (1978) model. Again, more coherence at the text base level led to better memory for the text. McNamara and Kintsch (1996), using the same original text and principled revision, also found an advantage for the more coherent text in terms of recall and answering multiple-choice questions. These studies establish that text-structure omissions can create problems for readers, even though automatic inference and knowledge retrieval processes can bridge them in most cases. Nevertheless, we assume that such omissions can be readily supplied by readers, so long as the text is reasonably well written and appropriately targeted. We are more concerned with content-structure omissions.

Content-structure omissions occur when the text does not explicitly state how elements of the situation it is describing are connected to one another. Such omissions are typical, and even desirable. That is, it would be a very unusual (and boring) text that included *all* of the information needed to completely represent its topic. Texts generally leave out information that a typical reader could supply through background knowledge or inference, in order to avoid seeming redundant (Kintsch, 1998). Sometimes texts also omit information that the typical reader cannot supply, as analyses of real-world descriptive texts have shown (Beck, McKeown, Sinatra, & Loxterman, 1991; Britton & Gulgoz, 1991). For example, if a text states that "The septum divides the heart length wise into two sides," (Towle, 1989), but does not relate this to keeping oxygenated and deoxygenated blood separate, the reader may not be able to infer this function about the septum.

Not surprisingly, text revision studies establish that content-structure omissions may lead to problems. Beck and her colleagues (Beck et al., 1991) revised social studies texts aimed at elementary school students. Revisions to the texts included establishing causal connection between events, and were thus aimed at establishing connections between elements of the situation the text described (pre-Revolutionary American history). Readers of the revised, more coherent texts performed better on tests of recall and comprehension. Subsequent studies using similar styles of revision yielded mixed results. Sinatra, Beck, and McKeown (1993), using a text on whaling, did not find an influence of the text revision on recall. One possibility for this divergent result, they hypothesized, was that the subjects had more background knowledge on this subject than they did on the American Revolution, therefore they did not need the addition of causal relations in the revised text. This interpretation was later confirmed in a study by McNamara, Kintsch, Songer, and Kintsch (1996). They found that high-knowledge subjects improved their comprehension on a less coherent text, whereas low-knowledge subjects needed a more coherent text. These findings suggest that high-knowledge subjects might be engaged in more effortful processing by drawing on prior knowledge to substitute for what was missing in the text. Thus, self-explanation inferences are consistent with both the situation model building perspective (especially in the case of high-knowledge subjects) and the mental model revision perspective.

Intentional Controlled Processes in Situation Model Building and Mental Model Revision. Kintsch (1998) therefore allows that when the comprehension process does not go smoothly, some (nonautomatic) effortful controlled processes may be needed to create a coherent representation of the situation described by the text. These controlled processes encompass what are typically called inferences, and in the context of this volume, we call them intentional. SEIs would be observable examples of controlled processing, in this view.

In the situation model building view, intentional, or controlled, inferences may occur when a reader perceives a problem in his or her understanding of the situation described by the text. Consider the following sentence from Towle (1989): "When a person has an infection, the number of white blood cells can increase tenfold." Although they have just read (four sentences back) that white blood cells "defend the body against disease," readers may not automatically invoke a connection between infection and disease. And they may not see the connection between more white blood cells and fighting an infection. In these cases, readers may search for prior knowledge that resolves this content structure gap. For example, they may recall being taught that infections cause disease. They may also try to induce a solution to the problem by imagining a possible element of the situation and seeing how it integrates with the rest of the mental model. For example, they may postulate that more white blood cells allow the body to combat more infectious agents. Or the element of the model needed to solve the problem may be arrived at by a combination of retrieval and reasoning, such as considering a similar situation and reasoning by analogy. These intentional processes of retrieval, integration, and reasoning by analogy do encompass Chi's definition of SEIs. Thus, SEIs could fit into the CI framework as a form of controlled inferences that extend the normal comprehension process by bringing in both new (generated), and old (retrieved) knowledge.

However, there may be a subtle difference in that SEIs, as an intentional process, are brought to bear when the reader perceives not so much a content structure gap in the text, but a discrepancy or conflict between the content of the text and the content of one's domain model (Chi, 2000).

The Role of Prior Knowledge in Situation Model Construction for Novices and Experts

Comprehension in the CI model is a process of integrating information in the text with related prior knowledge in order to create a situation model. Whether that prior knowledge serves as background or foreground to the comprehension process is a matter of expertise. This distinction is important for understanding SEIs in situation model construction because it speaks to the role of prior knowledge in SEI production. For the novice, comprehension is dominated by the text, with background knowledge brought in piecemeal on the basis of the words in the text. Kintsch (1998) referred to this as *text base dominated comprehension*.

A domain expert, on the other hand, automatically links the information in the text to a wealth of other knowledge, so that the situation model that is created may be structured on the basis of existing schemas and knowledge, with new information just filling in slots in those structures. When prior knowledge is activated, it provides routes to retrieval of other prior knowledge. Therefore, the more expert the reader is in the domain, the more these pathways are quickly and automatically activated, and the more they are tightly linked. In situation-dominated comprehension, then, well organized and practiced prior knowledge tends to dominate comprehension. That is, the expert reader's existing model of the domain takes center stage in the comprehension process, even as he or she absorbs new information about the domain contained in the text being read. For example, if a circulatory system novice reads that "The heart pumps blood," and then, 20 sentences later, reads that "Blood enters the heart through the left atrium," the reader may not make a connection between the two (i.e., it is the same blood). A more expert reader, however, would have already activated some mental model of the blood's circulation, so that the latter sentence fits neatly into a structure already activated in working memory. Thus expertise, and the resulting situation-dominated comprehension, should enable readers to automatically resolve content-structure omissions, successfully creating a situation model without recourse to controlled processes, including SEIs.

COMPARING SITUATION MODEL CONSTRUCTION AND DOMAIN MODEL REPAIR

The mental model revision view and the situation model construction view differ in that the former treats the novices the same way as the latter treats the experts, in that both novices and experts come into the learning situation with prior mental models, but with the added twist that novices have flawed mental models whereas experts have largely correct mental models. Thus, the two views previously outlined are largely compatible, and we could even view them as complementary, with the exception that they address different issues. Because experts are likely to know the correct mental model, the issue of repairing their mental models does not exist for the situation model construction view. Moreover, the situation model construction view describes the comprehension process, and the mental model revision view describes the repair process, which is activity beyond comprehension that addresses problems in the situation model. Thus, the simplest way of combining these two views would be to assume that readers create a situation model, closely tied to the text, while reading, and then use that model as the basis for comparison and repair of the domain model. But there are several sticking points that suggest that the synthesis of these two approaches is not quite so simple.

In brief, the mental model revision view assumes an activation of one's existing mental model, even for a novice with a flawed domain model. This means that a flawed domain model is predicted to have a strong influence on learning and that intentional processes such as SEIs will be directed at that flawed model. In contrast, the situation model building view

assumes activation of an existing domain model only for an expert; and the flawed models of novices therefore have little influence on the learning process; and intentional processes will be focused on repairs of problems in the text. Thus, the situation model building view basically describes two situations: the novice with low background knowledge and the expert with high background knowledge. The mental model revision view discusses a third option, cases in which novices have a coherent but flawed conception.

At a more general level, the difference between these two views boils down to what is in the foreground of the learning process and what is in the background. In a text-base dominated situation model construction process (in the case for novices), the text is the foreground of what is being learned, and prior knowledge is background knowledge. From the standpoint of mental model revision, however, this perspective is reversed. The existing domain model is the focus of the learning process, and the text is considered as it impacts that model. Putting the reader's domain model in the foreground of the comprehension process is actually not at all incompatible with the CI model. In Kintsch's (1998) terms, this is the case of situation-dominated comprehension, described earlier. The representation being constructed is dominated by the reader's well-organized knowledge of the text's topic. This is essentially equivalent to saying that the reader's domain model, not the text, guides the comprehension process. So put in the terms of the CI model, the mental model revision view claims that self-explanation reflects situation-dominated processing, despite a lack of expertise. This would predict activation of an existing domain model, a strong influence of flawed domain models, and a self-explanation process driven by the domain model and not the text. The remainder of this chapter addresses each of these points in more detail and considers some evidence that bears on these issues.

What Is Activated During Reading?

The mental model revision and situation model construction views make different assumptions about what prior knowledge is activated during reading. By activation we mean something akin to Ericsson & Kintsch's (1995) long-term working memory, knowledge that is readily available for incorporation into the mental model under construction. A central assumption of the mental model revision approach is that readers are working on their domain model as they read, and therefore must activate all or part of a coherent prior model, not just the minimum related information necessary for comprehension. That is, each activation is targeted at either the entire mental model or portions of it, so that the knowledge that is activated in reading successive sentences is coherent (and/or connected).

This activation of a coherent model is not based on expertise and is assumed even for the novice with a deeply flawed domain model. By contrast, the CI model predicts only targeted activation of prior relevant knowledge for the novice, based on close associations to the propositions underlying the text. This implies that the various associations activated with the reading of successive sentences need not be coherently connected. For the novice, comprehension should be text base dominated, that is, closely tied to the text and not to any prior domain model. Moreover, there should not be any coherence in the knowledge activated. For the experts, on the other hand, comprehension should be situation dominated, in that a coherent domain model can be activated. Thus, the situation model construction view for the experts is analogous to the mental model revision view for the novice, with the exception that novices may work with flawed models.

Both perspectives predict a strong influence of prior knowledge for more expert readers. The correctness and elaborateness of the resulting mental model should be highly dependent on background or prior knowledge, whether it is activated based on expertise or effort. Thus expertise studies cannot discriminate between these two views. For example, McNamara et al. (1996) gave middle school students with more or less background knowledge about the circulatory system a text on heart disease that was varied in both local and global coherence. Not surprisingly, the higher knowledge readers did better on tests of recall, on question answering, and on problem solving. But the extent of the advantage depended on the coherence of the text. Given a high-coherence text, there was only a slight advantage in free recall for the high-knowledge readers, but given a low-coherence text, the gap in recall between low- and high-knowledge readers widened substantially. These results confirm that having more domain knowledge leads to better comprehension, at least in part because the knowledge compensates for deficiencies in the text. But they do not discriminate whether a coherent domain model is activated or only relevant targeted associations are activated.

Both perspectives also predict that more effortful processing while reading has a payoff, especially for high-knowledge readers. McNamara et al. (1996) found a consistent pattern of improved recall for more coherent texts when they measured text-base-level memory, but the pattern was different for problem solving questions, designed to tap the situation model. Low-knowledge subjects still performed better on these tests when provided with texts that were more coherent. But the high-knowledge subjects actually did better with the baseline, minimally coherent text. Evidently the lack of connections in the text forced those readers to supply their own structure and content-filling knowledge, which resulted in a better situation model. Another study also provided evidence that greater activation of prior knowledge can be achieved through effort as opposed to expertise. Mannes and Kintsch (1987) provided readers with an outline of a short text's topic, which involved the industrial applications of bacteriology. The outline served as a manipulation of prior knowledge in this study. It was either based on and thus consistent with the text, or based on a related article from an encyclopedia and therefore inconsistent with the structure of the text. The information content of the two outlines was the same. Subjects given the inconsistent outline did better on reasoning tasks designed to rely on their situation models. Thus the inconsistencies between text and the structure of prior knowledge (from the outline) appeared to spur processes that created a more useful situation model. Chi (2000) also proposed that noticing conflicts between one's domain model and the text drives effortful intentional processes such as SEIs. These studies also support the assertion in the mental model revision view that greater activation of prior knowledge can be achieved through effort as opposed to expertise. However, they do not discriminate between a coherent model activation and a greater quantity of related knowledge activation, because the tests of knowledge were based on the normative, correct, model presented in the text.

Enforced self-explanation may serve a role similar to that of the inconsistent outline, or less coherent text, by also forcing readers to be more mindful of their existing domain knowledge (Chi & Bassok, 1989; Kintsch, 1994). Enforced production of self-explanations is certainly more effortful than not producing self-explanations, and the results (e.g. Chi et al., 1994) show greater gains in knowledge for students who self-explain. But again, gains in correct answers to questions do not tell us whether greater learning was achieved by more successfully incorporating the text into an existing domain model, or by injecting more of the domain-relevant knowledge into a situation model based on the text. The real test of whether students activate an existing mental model while self-explaining or whether they merely retrieve and incorporate relevant knowledge is what becomes of flawed domain models.

What Is the Influence of a Flawed Domain Model and Incorrect Prior Knowledge?

Flaws in the existing domain model play different roles in the mental model revision perspective and the situation model construction perspective. In the former case, a coherent domain model (or portions of it) is activated, even for a novice with a flawed model. Understanding is driven by the goal of assimilating new information with the existing domain model, flaws and all. If conflicts are noticed, then the domain model has to be repaired. Thus, the mental model revision perspective predicts that it is possible that the text information fails to successfully repair the prior flawed domain model, and that the resulting domain model continues to be flawed in a coherent way. This prediction is supported by evidence in Chi et al. (1994, Table 5). In that study, we found that more than half of the students (13 out of 24) continued to display flawed mental models in their understanding after reading the circulatory text, even though their flawed mental models were much improved.

In contrast, the situation model construction perspective views the text-based comprehension of the novice as driven by specific nodes and links of the text, with individual relevant pieces of background knowledge associated with the nodes and links, activated to enrich the text-base representation. Because the situation model arises from a piecemeal integration of relevant and related knowledge to the text-base representation, it is not clear how the resulting situation model, if incorrect, can be coherent. That is, if background knowledge is incorrect, then the resulting situation model is incorrect at places where the relevant background knowledge is incorrect. The implication of the CI processes is that the resulting misunderstanding cannot be "coherent" because incorrect background knowledge is brought to the text-base representation in a piecemeal way, depending on the nodes and relationships expressed in the text sentences.

For example, consider the student whose model of the circulatory system is based on a single loop. Blood goes from the heart to the lungs to get oxygen, then from the lungs to the body, where the oxygen is depleted, and then back to the heart. This model consists of a number of component functions (heart pumps blood to lungs, lungs oxygenate blood, blood travels from lungs to body, etc.) that are linked to each other (The heart pumps blood to the lungs SO THAT the lungs can oxygenate the blood, etc.) Although it is flawed, this model can be quite coherent in terms of its underlying assumptions that are used to make consistent predictions. Most of these specific nodes and links are correct and will be echoed by the text. Thus in the situation model view, a good deal of the students' existing knowledge is activated because it is closely linked to the text. However, the central organization feature of the model, the single loop, should not be activated. The text will also not mention a single loop, nor will it mention the blood traveling from the lungs to the body, because these are both wrong. Thus these incorrect nodes and links are not alike.

In the mental model revision perspective, however, the coherent but incorrect single loop model is activated, so that readers will essentially try to fit the correct information in the text into their incorrect organization. Much of what is in the text will be perfectly compatible with that flawed model, because most of the specific nodes and links in the model are correct. And the text will not mention the single loop, even to say that it is wrong. So the readers will either notice that specific functions in the text (e.g., the pulmonary artery carries blood from the heart to the lungs) contradict the global organization of their model, or they will fail to integrate those nodes into their domain model, thereby leaving the resulting domain model a still-coherent and somewhat enhanced version of a globally flawed model.

What Is the Goal of Intentional Processes?

Intentional processes, including SEIs, are distinct from automatic processes in comprehension in that they are directed at solving a problem. That problem might be in the text, in the form of text or content structure omissions, or it might be in the domain model, in the form of misinformation or a gap in knowledge. As we stated earlier, content-structure omissions consist of gaps in local coherence at the text-base level, and should not require any intentional processes to repair so long as there is adequate background knowledge to cover them. So in this section we consider whether self-explaining inferences are driven by content level problems within the text, or by flaws in the existing domain model.

Text Coherence and SEI Production. A situation-dominated comprehension or the mental model revision view would predict that self-explanations are driven by problems in the domain or situation model (in the sense that it conflicts with the text), rather than problems in the text. If self-explanations were driven by problems in the text, then in principle we would expect to see different readers self-explaining at the same troublesome points in the text, as readers would use self-explanations to resolve these difficulties. Moreover, if it is difficulty with the text itself that is driving self-explanation, there should be some consistency among different readers of the same text, especially readers with similar backgrounds. As we alluded to earlier, Chi (2000) reanalyzed data from both the Chi et al. (1994) and the Chi et al. (1989) studies, and found this was not the case. There was no consistent pattern of when self-explanations were produced across subjects. Instead, a very idiosyncratic pattern of self-explanations was produced by each student, suggesting that problems in the text are not the source self-explanation generation. This was the case despite the fact that all of the subjects read the same text under the same conditions. This pattern of individual differences in the idiosyncratic locations at which explanations were generated was obtained for both spontaneous explainers and enforced explainers.

Using the data from deLeeuw's (2000) dissertation, we were able to replicate this idiosyncratic pattern in a more systematic way. Subjects in this study were seventh graders, reading the same circulatory system chapter (Towle, 1989) as in Chi et al. (1994). In this study, however, there was a second version of the text created using an analysis of content-level incoherence or omissions. In places where the text failed to explicitly connect the function of one component to those of the others in a causal chain, or failed to explicitly place a component in a hierarchy of system parts, these details were added to the revised version of the text. The revised version was therefore more explicit in connecting all of the components of the circulatory system, both functionally and hierarchically. Thus, the revised version had all the content omissions filled. Students reading either version of the text were prompted to self-explain after each paragraph, 16 times in all. (An additional 18 students were not prompted to self-explain, but their results are not discussed here). The verbalizations they produced were later segmented into roughly sentence size, and each segment was classified in one of five categories. These were summaries, paraphrases, self-monitoring statements, elaborations that did not add information about the circulatory system, or self-explaining inferences (SEIs). SEIs contained information about the circulatory system not presented in the text (or not yet presented). The majority of utterances (80%) were summaries or paraphrases of the text. Only 5% of them were classified as SEIs.

The protocols for each student were combined to yield a count of how many SEIs were produced at each prompting location in the text. This would show if any problems in the text led to a higher number of SEIs for that portion of the text. However, no locations yielded significantly higher numbers of SEIs than any other, based on a one-way ANOVA with 16 levels, one for each prompt. The only difference that approached significance, $F(15, 225) = 1.629$, $p = .0675$, was entirely due to two prompts (10 and 14) that drew no SEIs from any subject. These passages concerned William Harvey's discovery that the circulatory system formed a closed double loop, and the composition of the blood. Although these two paragraphs drew fewer SEIs than others, no location drew significantly more SEIs, which would have been the indication that a lack of text coherence at particular location was the driving force behind SEI production. For these students and these texts, at least, it was not.

The same analysis revealed that overall text coherence also did not influence the production of SEIs. Because the revised text in this study explicitly provided functions and connections between functions that were lacking in the original, it had fewer content-structure omissions. If those omissions in the original text were an impetus to self-explain, we would expect that students assigned to read the original text would self-explain more, overall, than students reading the revised text. However, the number of SEIs produced in response to the original text (mean = 4.00) was no greater than the number produced in response to the revised text (mean = 4.22), $F(1, 225) < 1$, n.s. Subjects in this study were not producing SEIs in response to a lack of coherence in the text.

These results do not mean that students never produce SEIs, or use other intentional processes, in response to problems in the text. The McNamara et al (1996) study mentioned earlier suggested that they do. But the fact that SEIs were produced, and were not text driven, lends indirect support to the view that they were produced in response to domain model flaws. More direct support for this hypothesis is based on an analysis of the domain models subjects brought in to this study.

Domain Model Structure and SEI Production. If the production of SEIs did not reflect the structure of the text, did it reflect the structure of students' domain models? The mental model revision view predicts that it should reflect the structure of the domain model. In order to test whether SEIs are generated as a function of the structure of the domain model, we need to characterize the structure of a domain model.

In order to capture the structure of students' prior domain models, each of the students in the deLeeuw (2000) study underwent a detailed interview in which they responded to a series of prompts about each of 31 components of the circulatory system. Transcripts of these interviews were translated into a set of propositions concerning the functions of each component. These propositionalized representations were then further analyzed as described next.

Perhaps the most effective method to capture students' domain model is to analyze the transcripts in such a way as to depict the model, as was undertaken in Chi et al. (1994). In a multistep procedure, Chi et al. (1994) identified and classified students' mental models of the circulatory system according to the number of loops in the subject's model of blood flow, whether lungs played a role in oxygenating blood, whether the chambers of the heart were assigned appropriate functions, and similar features. The range of classifications was from a no-loop model in which blood was pumped from the heart and did not return, to a double loop model in which substantially all of the major features were correct. Also, it is not obvious how the production of SEIs should correspond to a specific prior model, although one could assume that the more flawed a mental model is, the more SEIs may be needed to repair that model. However, such direct correspondence does not take into account the fact that students often miss opportunities for repair (thereby not producing any SEIs) because they overlooked conflicts between their flawed domain model and the text information (Chi, 2000). Thus, a new method of assessing structure is needed. Here, we characterize the structure of a domain model by three properties: the amount of missing knowledge, the amount of wrong knowledge, and connectedness.

The domain model revision view predicts that SEIs will be produced in response to missing knowledge in a reader's domain model. However, missing knowledge was very unlikely to be filled in unless it was present in the text, so missing knowledge was defined as specific functions of circulatory system components that were mentioned in the text but not in the subject's pretest. The texts were analyzed in much the same way as student interviews, so that a set of propositions about the functions of the same 31 components covered in the interviews was created. The number of propositions explicitly laid out in the original text was 31. The amount of missing knowledge in a students' domain model was estimated by subtracting the number of functional propositions expressed in their pretest interview from that number. Students who expressed fewer functional propositions were rated as having more missing knowledge, and thus were expected to generate more SEIs.

The domain model revision view also predicts that SEIs will be produced when there are inconsistencies between the text and the reader's mental model. These are most likely to occur when the reader's knowledge is wrong. Wrong knowledge was assessed by counting the number of wrong arguments in the functional propositions. For example, if a student said that "the left side of the heart pumps deoxygenated blood" (pump [location [heart, left side] type [blood, deoxygenated]]), only a single argument (deoxygenated) was counted as wrong. However, if a the student said that "the heart oxygenates blood" (add [heart, oxygen, blood]), the entire proposition—all three arguments—was counted as wrong, because that function is not actually performed by that structure. Students with more wrong arguments were expected to generate more SEIs.

Another property of structured knowledge is its connectedness. More connections yield a richer knowledge structure, and a richer structure should provide both more routes to the retrieval of prior knowledge and more of a basis for knowledge generation. The connectedness of students' prior domain models was assessed by looking at enabling links from one function to another. Enabling links exist where the function of one component enables the function of another component. For example, the heart pumps oxygenated blood to arteries, which enables the arteries to deliver the oxygenated blood to the capillaries, which allows the capillaries to deliver oxygen to the body cells, and so on. The number of components (such as the heart, lungs, septum) with links to and/or from them was divided by the number of functional propositions to give a connectedness score.

These three aspects of students' domain models—the amount of missing knowledge, the amount of wrong knowledge, and the connectedness in terms of the number of enabling links—were analyzed together in a single multiple regression, with the number of SEIs as the dependent variable. The results of this regression show that students' prior mental mod-

TABLE 3.1
Multiple Regression to Predict the Number of Self-Explained Inferences (SEIs)

*Independent variables**	*Coefficient*	*F value*
Overall regression	r^2 = .600	**$F(3, 13) = 6.505$**
Missing functional propositions in pretest	**.422**	**$F(1, 13) = 9.554$**
Wrong arguments to propositions in pretest	**.480**	**$F(1, 13) = 13.281$**
Connectedness or links per proposition in pretest	**15.260**	**$F(1, 13) = 15.557$**
Text assignment (original / revised)	‡	$F(1, 13) < 1$
Intercept	**−17.993**	**$F(1, 13) = 12.454$**

Note. ‡Factor removed in stepwise procedure, $F < 4$.
*Reliable predictors ($p < .05$) are shown in **boldface**.

els did have a strong influence on how many SEIs they produced, in a pattern that is consistent with the mental model revision view. Table 3.1 presents the results of a multiple regression using the number of SEIs as the dependent measure. As predicted by the mental model revision view, missing, wrong, and connected knowledge in the pretest domain models had positive weights in the regression model and led to more SEIs. Thus, the overall structure of the domain model, as assessed by the amount of missing knowledge, wrong knowledge, and connectedness, was a strong predictor of how many SEIs were produced by each student.

Thus, in these data (deLeeuw, 2000), SEIs were associated with domain model problems and structure, but not with text problems. These results are consistent with the mental model revision view that a reader activates a coherent domain model while self-explaining, working on its flaws and depending on its structure. The goal of these SEIs appears to have been domain model repair.

SELF-EXPLANATION AND INCREMENTAL MENTAL MODEL CHANGE

Chi and her colleagues (Chi & Roscoe, in press; Chi, Slotta, & deLeeuw, 1994; Slotta, Chi, & Joram, 1995) made a distinction between two types of conceptual change required when learning science. These may be called radical conceptual change and ordinary, or incremental conceptual change.

Radical conceptual change involves completely replacing old concepts with new ones, because the target scientific concept is incompatible with the existing "folk" concept. (*Replacing* means to consider an alternative conception.) The radical conceptual change required to conceive of electricity as a kind of process as opposed to a kind of substance, for example, is a radical one. This requires a wholesale ontological shift from a matter-based concept to a process-based concept (Chi, 1997). This kind of radical conceptual change is probably not accomplished through self-explanation. Because the shift required essentially involves replacing (or learning to ignore) old concepts, and building up new ones, it cannot be accomplished through incremental changes to an existing mental model.

But many scientific concepts require only a more modest shift in understanding. We have used the circulatory system, at least at the level taught in middle school, as an example of a domain that requires only *incremental conceptual change*. There are often false beliefs that must be changed about the circulatory system, for example, the belief that the heart oxygenates blood. Ideally, this should be replaced with the correct understanding that the lungs oxygenate blood. However, both of these beliefs remain firmly in the realm of substances, so conceptual change requires only a simple replacement of one piece of knowledge for another. We contend that this more incremental conceptual change is not that difficult.

The finding that the production of SEIs is dominated by students' domain models suggests that SEIs should be associated with conceptual change of the "nonradical" sort. That is, if readers are processing the text with their existing domain model in mind, it should be reflected in incremental changes to that model. To assess incremental changes, recall that in this study, subjects' pretest interviews about the circulatory system were coded into propositions about functions of the various system components. The same was done for posttest interviews, yielding detailed before and after representations of their knowledge. The analysis that follows focuses on the number of functional propositions gained from pretest to posttest.

The key issue in this analysis is whether a gain in functional propositions (from the pretest to the posttest interviews) was related to the production of SEIs while learning. It is possible that these self-generated explanations about functions added knowledge to the students' mental models that was later reflected in their posttest interview. To address this possibility specifically, SEIs were divided according to the kind of knowledge they embodied. The category of most interest was functional SEIs, which included statements about functions of the circulatory system components not explicitly stated in the text. These represented 52% of the total number of SEIs. The other categories were hierarchical (11%), spatial (8%), and connective (28%). This last category was for explanations that tied one function to another. Because functional SEIs were logically the most closely tied to gains in functional propositions, this was the only category of SEIs used as an independent variable to predict gains.

What factors led to gains in these subjects' mental models? This analysis follows the same procedure as the multiple regression to predict the

TABLE 3.2
Influences on Gain in Functional Propositions.

	Stepwise Elimination Regression	*Multiple Regression of All Factors*
Independent variables*	Coefficient / F value	
Overall regression	**r^2 = .594**	r^2 = .660
	F (2, 14) = 10.243	**F (5, 11) = 4.275**
	p < .01	**p < .05**
Missing functional propositions in pre-test	‡	.131 F (1, 11) = .535
Wrong arguments to propositions in pre-test	‡	−.018 F (1, 11) = .011
Connectedness or links per proposition in pre-test	‡	−1.630 F (1, 11) = .098
Text assignment (original/revised)	**3.540** **F(1, 14) = 9.235**	**3.508** **F (1, 11) = 8.048**
Number of SEIs about functions	**.732** **F(1, 14) = 10.872**	.684 F (1, 11) = 3.265
Intercept	**−2.056** **F(1, 14) = 4.494**	−1.578 F(1, 11) = .052

Note. ‡Factor removed in stepwise procedure, $F < 4$.
*Reliable predictors ($p < .05$) are shown in **boldface**.

number of SEIs (Table 3.2). Aspects of the subjects' pretest domain models (number of missing functions, number of wrong arguments, connections between functions) were used as predictors, along with the choice of original or enhanced texts and the number of functional SEIs. The results, presented in Table 3.2, show that both the number of functional SEIs and the choice of texts were reliable predictors of gains in functional propositions. (The results change only slightly if the total number of SEIs is substituted for functional SEIs.) Students benefited from reading the enhanced text, and also from explaining the text. The stepwise procedure eliminated all of the factors based on the pretest domain model, showing that the text and SEI production were more closely linked with gains than any of these.

However, Table 3.2 also shows the same regression run without the step-wise procedure, in effect treating the pretest factors as controls. The results for the text are similar, still showing a reliable effect of reading the enhanced version. The number of functional SEIs approaches significance in this case, $F(1, 11) = 3.265$, $p = .098$. This shows that the factors that predict SEIs overlap somewhat with the SEIs themselves in predicting gains. Subjects that were predisposed by their initial mental models to produce SEIs were also predisposed by these same factors to gain new functions from pretest to posttest. But SEIs also made a contribution to their gains, even after controlling for the differences in their pretest models.

Overall, these data point to two conclusions: that the enhanced text in deLeeuw (2000) was effective at helping students learn more about the functions of the circulatory system, and that producing SEIs also helped students learn more. In terms of mental model change, these two factors were the strongest predictors of proposition level additions to students' domain models.

DISCUSSION

In this chapter, we basically proposed three conjectures. First, we proposed that learning and understanding a (scientific) text may be viewed as a process of repairing a preexisting, coherent, but often flawed domain model, and not necessarily the building of a situation model. Second, we proposed that the role of self-explanations is to repair one's domain model, and not necessarily to resolve inconsistencies and discrepancies in a text. Third, we proposed that for some domains, understanding may often involve incremental mental model changes and not wholesale replacement of one mental model for another. Although our three conjectures may not be sharply differentiated from the alternative views, we posed them in such a contrastive way as a means of testing our ideas and predictions.

We presented some evidence to support our conjectures, although the evidence is by no means conclusive. It is merely suggestive that perhaps these conjectures might be true and worthy of further testing with more vigorous predictions. Moreover, we have not presented any evidence to directly contrast our conjectures and the alternative views. For example, to claim that a coherent preexisting mental model is activated while learning, one would have to show that the self-explanations, in composite, are coherent and are not merely a set of disjoint pieces of related knowledge.

We also did not fully address the question of what drives intentional processes. In the mental model view, intentional processes such as self-explaining are assumed to occur when the subjects perceive a conflict between the information in the text and their domain models. However, in order to notice such conflicts, the subjects must actively monitor what the text is saying and how it fits in with their mental model. Active monitoring can be enforced by asking subjects to self-explain. However, some subjects are perhaps more motivated to monitor their own comprehension even without such enforcement. However, we have no specific insights about the source of these individual differences.

There is one important caveat that should be pointed out. In the comprehension literature, there is a distinction between the topic that one is reading about (e.g., a disease such as septal defect), and the role of background knowledge (the circulatory system) on comprehension about such diseases. In the self-explanation literature, the domain model addressed is the one that the text topic addresses. That is, we looked at the way the students' domain model of the circulatory system changes as they read more about the circulatory system. It is not clear what the implication of such differences are for our conjectures.

In closing, we note that although Kintsch (1998) correctly conceived that "Comprehension is model building," we would add that learning is often model revision.

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