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Learning from Examples: Instructional Principles from the Worked Examples Research

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Worked examples are instructional devices that provide an expert's problem solution for a learner to study. Worked-examples research is a cognitive-experimental program that has relevance to classroom instruction and the broader educational research community. A framework for organizing the findings of this research is proposed, leading to instructional design principles. For instance, one instructional design principle suggests that effective examples have highly integrated components. They employ multiple modalities in presentation and emphasize conceptual structure by labeling or segmenting. At the lesson level, effective instruction employs multiple examples for each conceptual problem type, varies example formats within problem type, and employs surface features to signal deep structure. Also, examples should be presented in close proximity to matched practice problems. Moreover, learners can be encouraged through direct training or by the structure of the worked example to actively self-explain examples. Worked examples are associated with early stages of skill development, but the design principles are relevant to constructivist research and teaching.

The Historical Context

In recent years, learning from "worked examples" has received a considerable amount of attention from researchers (e.g., Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Ward & Sweller, 1990), particularly in such fields as mathematics, physics, and computer programming. Although there is no precise definition, worked examples share certain family resemblance (Wittgenstein, 1953). As instructional devices, they typically include a problem statement and a procedure for solving the problem; together, these are meant to show how other similar problems might be solved. In a sense, they provide an expert's problem-solving model for the learner to study and emulate. Examples typically present solutions in a step-by-step fashion (see Figure 1). In many cases, worked examples include auxiliary representations of a given problem, such as diagrams.

PROBLEM TEXT: From a ballot box containing 3 red balls and 2 white balls, two balls are randomly drawn. The chosen balls are not put back into the ballot box. What is the probability that a red ball is drawn first and a white ball second?

SOLUTION:

STEP 1:

Total number of balls:	5
Number of red balls:	3
Probability of red ball on first draw:	3/5

STEP 2:

Total number of balls after first draw:	4
Number of white balls:	2
Probability of white ball on second draw:	2/4

STEP 3:

Probability that a red ball is drawn first and a white ball is second: 3/5*2/4 = 6/20 = 3/10

ANSWER*:* The probability that a red ball is drawn first and a white ball is second is 3/10.

FIGURE 1. *Worked example from Renkl, Atkinson, and Maier (2000)*

Even though learning from worked examples has recently attracted much attention, the notion of learning by example is not new. Indeed, it has been a major theme in educational research for at least the past four decades. During the mid-1950s to the 1970s, cognitive and educational psychologists adopted the learning-by-example paradigm to examine and describe the processes involved in concept formation (e.g., Bourne, Goldstein, & Link, 1964; Bruner, Goodnow, & Austin, 1956; Tennyson, Wooley, & Merrill, 1972). While the examples employed by these researchers were dissimilar to worked examples in many respects, nevertheless, they shared the same fundamental purpose: to illustrate a principle or pattern. A typical study of concept learning by example measured students' ability to identify a member of a target concept after viewing numerous instances and noninstances of it, to learn whether students could successfully derive the underlying concept common to the examples. From the perspective of educational psychologists, these studies could inform educational practice, particularly by showing how examples should be selected, presented, and sequenced (for review, see Tennyson & Cocchiarella, 1986). This focus on presentation and sequencing of examples paralleled the call for empirical investigations articulated in classic position papers, such as Bruner's (1966) *Toward a Theory of Instruction* and Glaser's (1976) *Components of a Psychology of Instruction: Toward a Science of Design.*

Although a considerable amount of research in the mid-1970s was dedicated to identifying ways to facilitate concept learning, a growing number of cognitively oriented educational researchers began to look beyond the goal merely of acquiring discrete concepts. Instead, researchers turned their focus to more complex forms of knowledge and learning (Brewer & Nakamura, 1984). Topics of interest included studying how experts and novices used knowledge to interpret experience and solve problems in domains such as chess, algebra, physics, and geometry. Research indicated that experts typically focus on deeper structural aspects of problems, whereas novices are often misled by surface features (e.g., Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Rees, 1982; Silver, 1979). Often, the concept of the schema (Rumelhart & Ortony, 1977; Silver & Marshall, 1990) was used to account for performance differences between experts and novices (cf. VanLehn, 1990; Chi et al., 1981; Chi et al., 1982; Hinsley, Hayes, & Simon, 1977; Silver, 1979). Schemas were conceived to be complex memory structures possessed by experts that enabled them to recognize a problem as a member of a class (e.g., a type of physics problem) and retrieve an interpretation and procedure appropriate for that class.

Working in this milieu, Sweller and his colleagues (e.g., Mawer & Sweller, 1982; Owen & Sweller, 1985; Sweller & Levine, 1982; Sweller, Mawer, & Howe, 1982; Sweller, Mawer, & Ward, 1983) began investigating how students learn schemas, patterns that facilitate problem solving, through conventional, practice-oriented instruction. These studies focused on methods of increasing novices' awareness of problem structure through practice (Owen & Sweller, 1985; Sweller et al., 1983). It is important to note that this research was conducted at a time when problem-solving practice was a preferred instructional approach, endorsed by many prominent educators and researchers. As a noted mathematics education professor declared, "The best way to teach children how to solve problems is to give them lots of problems to solve" (Van Engen, 1959, p. 74). Further, the research showed that the study of expertise was consonant with this thinking. After studying chess experts, Chase and Simon (1973) concluded that "practice is the major independent variable in the acquisition of skill" (p. 279).

However, Sweller's research program soon accumulated empirical evidence showing that traditional, practice-based problem solving was less than an ideal method for improving problem-solving performance when compared to instruction that paired practice problems with worked examples (Cooper & Sweller, 1987; Sweller & Cooper, 1985). Laboratory protocol studies revealed that when presented with traditional practice exercises, students tended to employ typical novice strategies, such as trial and error, while students presented with worked examples before solving often employed more efficient problem-solving strategies and appeared to focus on structural aspects of problems. A number of researchers, again including Sweller and his colleagues, investigated the efficacy of using more worked examples in classroom instruction. Zhu and Simon (1987) conducted the first, and possibly the most widely cited, of these studies. Studies by Carroll (1994) and Ward and Sweller (1990) also provided evidence in favor of worked-example instruction in the classroom rather than strictly problem-solving practice.

Sweller's research program, along with the classroom investigations noted above, motivated a new and productive strand of research, widely called "worked examples research," and it is this literature that serves as the basis for this review. Although Sweller, van Merrienboer, and Pass (1998) recently published a review addressing instructional design issues related to worked examples, they focused on literature published by Sweller and his colleagues and only on instructional principles derived from Sweller's cognitive load theory. Their review thus omitted a substantial portion of the literature and much that has been learned about worked examples instruction, such as individual differences in example processing (self-explanations), and the impact of situational factors. We did not limit our analysis to the research findings from one research group or theoretical perspective, but instead searched for a set of design principles that could be derived from a broader set of studies representing additional research groups and theoretical viewpoints. Moreover, our goal was to move beyond communicating to the worked examples research audience only. We wished to draw attention to how the findings from the worked examples paradigm can inform a larger educational community that is using and investigating a broad range of complex instructional paradigms that employ problem solving and examples to promote learning.

We begin our review by justifying our belief that the worked examples research has potentially broad implications for educational practice. We then "situate" the place of worked examples in the context of a widely accepted theory of learning. Next, we review the worked examples literature and derive a set of instructional principles from this work. We then propose a framework representing a causal model incorporating the major factors that have been shown to influence learning from worked examples. In the fourth section of this review, we interpret this model with respect to its implications for other instructional approaches and in this context, present our recommendations for re-directing research dealing with example-based learning and instruction.

The Worked Example Paradigm as Basic Research

Acknowledging that much (though by no means all) of the worked examples research to date has been conducted in controlled laboratory settings using textbook problems from mathematics and science, we begin by reflecting on the "place" of such controled experimentation within the broader educational research enterprise. The contention that controlled, experimental studies could have implications for the complex, bustling world of real classrooms can be challenged on the grounds that important social, physical and cultural contexts shape student development and are often "controlled out" of educational experiments. Of course, laboratory findings alone cannot inform educational practice. Yet there is very strong evidence (see, e.g., Bruer, 1993; McGilly, 1998) and argument (Shuell, 1996) that controlled experimental research grounded in cognitive science has substantially improved educational practice. The 1998 volume edited by McGilly provides stories of many widespread and successful classroom reforms – led by such scholars as Carl Bereiter, John Bransford, Ann Brown, Joseph Campione, Howard Gardner, Jim Minstrell, Marlene Scardamalia, Robert Sternberg, and others – that were founded on a laboratory-based cognitive science. Chapters describe how a process that involved the testing, in classroom settings, of fundamental ideas about learning and development drawn from basic cognitive research advanced knowledge about instructional practice. Reciprocal teaching (Palincsar & Brown, 1984) is a classic example of a cognitively-based instructional approach, first investigated in a controlled setting, that has been adopted widely and proven immensely successful classroom contexts.

We hold that the explicit understanding of learning processes obtained through controlled experimentation, including laboratory experimentation, is an important part of the scientific knowledge base about teaching and learning, which, in turn has had a significant positive impact on instructional research and practice in classrooms. Transfer from laboratory to classroom is possible because, while there are many differences between laboratory and classroom environments, there are also many constants across settings in terms of students' basic neural and cognitive processing, as well as the structure of interventions and materials investigated. Similar arguments were made by Scribner (1984), who held that models for practical problem solving in working contexts could not be developed "without reiterative cycles of both laboratory and non-laboratory based studies" (p. 37). It is in this vein that we present the worked examples research as a cognitively-oriented experimental program that has produced findings of relevance and importance that should be communicated to the broader educational research audience.

Worked Examples and Acquisition of Cognitive Skills

The worked examples literature is particularly relevant to programs of instruction that seek to promote skills acquisition, a goal of many workplace training environments as well as instructional programs in domains such as music, chess, athletics, programming, and (arguably) basic mathematics. From this viewpoint, learning from worked examples is of major importance in *initial* stages of cognitive skills acquisition. What we mean by *initial* skills acquisition can be more precisely defined by referring to Anderson, Fincham, and Douglass (1997). These authors proposed a four-stage model within a well-known cognitive theoretical framework called *ACT-R* and argue that skills acquisition involves four overlapping stages. In the first stage, learners solve problems by analogy, that is, they refer to known examples and try to relate them to the problem to be solved. In the second stage, learners develop abstract declarative rules, verbal knowledge that guides their problem solving. Only after longer practice do they move to the third stage, in which performance becomes smooth and rapid. When this stage is achieved, learners no longer have to follow their learned verbal rules, which is a slow process, but can deal with familiar problems or aspects of problems quickly and automatically, without using many attention resources. This is possible through practice—the verbal memory evolves to incorporate a different, procedural form of memory. In the fourth stage, learners who have practiced many different types of problems have many examples in mind. Hence they can often retrieve a solution quickly and directly from memory. The authors emphasize that these stages overlap in the sense that a specific learner's flexibility in using different methods, such as analogy or abstract rule, depends upon the familiarity of the specific problem at hand.

From the viewpoint of skills acquisition, then, the importance of studying examples relative to pure problem solving practice is very high when a student is in the first stage (analogy) or is beginning to enter the second stage (abstract rules of learning). Studying worked examples is not the preferred method when the instructional goal is to facilitate the attainment of the third stage, automatic performance, where problem solving practice is of critical importance. However, even after reaching the fourth stage, experts may study complex performance by other experts in order to learn stylistic techniques or fine-tune their own complex performances.

Teaching by Worked Example: Research and Instructional Principles

Although the early research demonstrated that worked examples were instructionally effective, our review suggests specific factors that moderate their effectiveness. These include (1) intra-example features, in other words, how the example is designed, particularly the way the example's solution is presented, (2) inter-example features, principally certain relationships among multiple examples and practice problems within a lesson, and (3) individual differences in example processing on the part of students, especially the way in which students "self-explain" the examples.

Intra-Example Features

Researchers (e.g., Catrambone, 1994b; Catrambone & Holyoak, 1990; Mwangi & Sweller, 1998; Ward & Sweller, 1990; Zhu & Simon, 1987) have suggested that the design or structure of worked examples plays a critical role in their effectiveness. In fact, Mwangi and Sweller (1998) suggest that "the structure of worked examples may substantially compromise the benefits derived from studying them" (p. 174). In particular, how to integrate the various components making up an example appears to be critical. Principles of integration can be derived from three sources, the first of which is work that examines the integration of diagrams and text. The second is work that investigates the simultaneous presentation of diagrams and aurally presented procedures. Finally, studies investigating the effects of subgoal labels within examples have led to important design principles. We cover each of these in turn.

Integrating Text and Diagrams

While worked examples can play a crucial role in guiding the learning process (Carroll, 1994; Cooper & Sweller, 1987; Paas & Van Merrienboer, 1994; Sweller & Cooper, 1985; Ward & Sweller, 1990; Zhu & Simon, 1987), Sweller and his colleagues (Mwangi & Sweller, 1998; Tarmizi & Sweller, 1988; Ward & Sweller, 1990) suspected that, because of their structure, some worked examples might burden the student's working memory. The imposition of a heavy cognitive load was thought to negate the benefits of studying worked examples. In particular, these authors focused on the cognitive load imposed on learners studying geometry worked examples, which required the learners to integrate the information from diagrammed problems with textual explanations referring to the same concepts. They proposed that instructional material requiring a student to split attention among multiple sources of information might impose a heavy cognitive load. Tramizi and Sweller (1988) labeled this phenomenon the *split-attention* effect and hypothesized that it interfered with the student's acquisition of schemas representing the basic domain concepts and principles that students should learn from examples.

Tarmizi and Sweller (1988) further hypothesized that requiring students to split their attention between multiple sources of information during example-based geometry instruction would decrease subsequent problem-solving performance, even for those students provided with worked examples. To examine this supposition, they assigned participants in one experiment (Experiment 3) of a multi-experiment study to a conventional problem solving condition (control); students in an experimental worked-example condition were asked to solve six pairs of problems, where the six pairs of problems were similar to those in the control condition but with one notable difference, that the first problem of each pair was worked for them. During the learning phase, students in both conditions were given a fixed period of time to study their respective condition-specific material. The problems across both conditions involved two theorems from circle geometry and required the participants to process and integrate separately the problem statement, one or both of the theorems, and the problem diagram. In addition to looking for performance differences between the two conditions on a three-item posttest, such as time to solution and problem-solving strategy used, the authors also measured certain factors during the learning phase, such as the number of problems processed, as well as the number of errors and the time to solution on practice problems.

Results of this experiment supported Tarmizi and Sweller's (1988) hypothesis that requiring students to integrate multiple sources of information in instruction would be ineffective, even when presented in a worked-out format. In contrast to the earlier studies, which detected a clear advantage for the worked example format (Cooper & Sweller, 1987; Sweller & Cooper, 1985), they found in this case no significant differences in favor of worked examples on any of the measures. Instead, they found a difference in favor of conventional problem solving on time-to-solution on the posttest. They concluded that the "guidance provided by worked examples not only failed to facilitate subsequent performance, it actually retarded learning" (Tarmizi & Sweller, 1988, p. 431). In sum, Tarmizi and Sweller found that the split-attention format, at least in the materials they tested, reliably reduced the advantage of worked examples compared to conventional problem-solving practice.

Following their discovery of the split-attention effect, Tarmizi and Sweller (1988) proposed that the "presentation of geometry worked examples in a format reducing the multiple sources of information should increase the facilitatory effect of the material" (p. 425). Examining this hypothesis in Experiments 4 and 5, they questioned whether presenting students with worked examples that integrate the diagrammatic problem representations and the textual explanations relevant to the diagram—thus alleviating the burden of the split-attention effect—was more effective than more conventional problem solving. Relying on essentially the same experimental design as in Experiment 3, the authors found that simply restructuring the worked example by integrating verbal explanations into a diagram enhanced learning in comparison to conventional problem solving and split-source worked examples. Tarmizi and Sweller concluded, "Worked examples that require students to attend to multiple sources of information which then must be mentally integrated are cognitively demanding and interfere with, rather than facilitate, learning" (p. 435). The solution to the split-attention effect that they proposed is to integrate textual explanations into the accompanying auxiliary representation wherever possible.

In a subsequent study, Ward and Sweller (1990) examined the impact of the split-attention effect, but with two slight modifications in the former study's design: They examined it under traditional classroom conditions and within the domain of physics. Making these modifications, they essentially replicated the findings of Tarmizi and Sweller (1988). In three long-term experiments conducted with students in a high school physics programs, they found that the split-attention effect was manifested when students were presented with worked examples in homework that required them simultaneously to attend to multiple sources of information related to geometric optics problems. But they found, as did Tarmizi and Sweller (1988), that simply reformatting the examples to integrate verbal explanations, such as the description of problem subgoals, enhances learning.

Integrating Aural and Visual Information

If integrating the visual elements in an example facilitates understanding, might integrating aural and visual presentation of material boost problem-solving performance and facilitate problem solving as well? In a recent study, Mousavi, Low, and Sweller (1995) addressed this question in a series of experiments by examining whether split attention might be mitigated by presenting geometry problem and proof statements in auditory, rather than visual, form. Although each experiment described in their study involved a slightly different manipulation of worked-example instruction itself, the various experiments shared a common design. First, during each experiment, the participants proceeded through a learning phase, where they were presented with two pairs of items, each consisting of a worked example and a similar practice problem. During this learning phase, the average time spent studying the examples and solving the practice problems, as well as the number of participants who were unable to solve each problem (i.e., nonsolvers), were recorded. This phase was followed by a four-item posttest, which consisted of two problems similar to the problems from the learning phase and a pair of transfer problems that required the participants to apply their knowledge in a novel way. As the participants solved the various posttest items, the average time spent solving each of the problems (i.e., posttest processing time) and the number of nonsolvers was noted in each experiment.

In Experiments 1 and 2, Mousavi et al. (1995) compared the effectiveness of three differently formatted worked examples: (1) visual-visual, where a geometry diagram and its associated statements (i.e., problem and proof) were both presented visually; (2) visual-auditory, where a diagram was presented visually and its associated statements aurally; and (3) simultaneous, where a diagram was presented visually and its associated statements were presented both visually *and* aurally. They found modest evidence that the mixed-mode formats *(both visual-auditory and simultaneous)* were superior to the more conventional single-mode format (visual-visual), since the students in the mixed-mode condition spent less time solving the test problems than their single-mode counterparts, even when the time spent studying the conditions was controlled. In Experiments 3 and 4, the visual-visual and visual-auditory formats were again used, but this time the diagram and problem statements were presented either simultaneously, as in Experiment 1 and 2, or sequentially. Across these two experiments, once again, the authors found that, irrespective of the presentation format, the processing time of the participants exposed to the mixed-mode examples was superior to that of their counterparts using single-mode examples, even when the study time was equalized across the mixed-mode and single-mode examples. In sum, the authors showed that learning—as demonstrated by the efficiency of subsequent problem-solving performance—was consistently enhanced by the dual-presentation mode. It is also worth noting that additional support for incorporating a dual-presentation mode into instructional material can be found in the research conducted by Mayer and his colleges (Mayer, 1997; Mayer, Moreno, Boire, & Vagge, 1999) on multimedia learning. In a series of studies, they have consistently found that a mixed-mode presentation format facilitates learning in scientific context.

Still, a caveat remains. A recent study by Jeung, Chandler, and Sweller (1997) found that under certain "high visual" conditions, structuring a worked example to include both visual and verbal modes did not represent an improvement over a visual-only worked example. The authors suspected that presenting visually complex geometry examples with auditory procedures required the learner to devote a significant portion of working memory to locating the portion of the geometry diagram to which the auditory statements referred. Jeung et al. tested this supposition, in part, by adopting two of the conditions from the Mousavi et al. (1995) study, the visual-visual condition and audio-visual condition. They also created a third condition by adapting the audio-visual condition to include a visual indicator that directed the learner's attention to the part of the diagram to which the audio—consisting of problem statements and proofs—was referring (audio-visual-flashing group). Students in the three conditions were exposed to a set of instructional materials (i.e., two example-practice problem pairs), with half of the students in each group being assigned high-search material and the other half low-search material. The complexity of the search depended upon the manner in which the geometry diagrams were labeled in the two examples, with the high-search material using twice as many labels as the low-search material to convey the same information. As Jeung et al. (1997) had predicted, although participants in the audio-visual condition solved several of the problems on the four-item posttest faster than their visual-visual counterparts when encountering low-search material, there was little or no effect for presenting information in dual modes under high-visual search conditions. However, the situation changed when a visual cue, such as a flashing highlight, linked auditory procedures to the relevant part of the complex geometry diagram. That is, the students presented with the set of audio-visual flashing examples outperformed their peers in the other two conditions. According to Jeung et al. (1997), simply adding electronic flashing to a dual-mode example can lead to enhanced learning, even under high-search conditions, by encouraging the learner to devote cognitive resources to understanding the example, as opposed to dedicating them to search and recognition.

Integrating Steps and Subgoals

Over the past few years, Catrambone (1994a, 1994b, 1995a, 1995b, 1996, in press; Catrambone & Holyoak, 1990) has carefully examined the way in which another instructional design enhancement, the structuring of examples to emphasize conceptually meaningful chunks of a problem's solution or subgoals, impacts learning. He has proposed that formatting an example's solution to accentuate its subgoals, by either affixing a label to them or simply visually isolating them, can assist a learner in actively inducing the example's underlying goal structure, which can guide a learner to discovering useful generalizations. Catrambone suggests that these structural cues enhance learning by encouraging learners to determine first the goal or function of the subgoals and then to explain to themselves why a series of steps are grouped together. This cognitive activity presumably helps promote induction of deeper structure representing domain principles, or schemas.

In his first study dedicated to examining the effectiveness of salient subgoals in worked examples, Catrambone and Holyoak (1990) asked college students to learn the Poisson distribution under two conditions: (1) highlighted, where the subgoals on four worked examples were made salient with annotations, or (2) not highlighted, where the same four examples were used, but without the subgoal-oriented annotations. The authors looked for differences between the two conditions in a six-item transfer posttest, which contained two problems similar to the worked examples and four problems that were not, but that could only be solved by making adaptations to the subgoals found in the examples. Thus, the last four items were novel problems that required the learners to formulate solutions that were distinct from those demonstrated in the training examples. Although the participants in both conditions performed comparably on all of the similar items as well as on most of the novel items, the participants in the highlighted condition outperformed their peers in the non-highlighted condition on one novel transfer item. The authors concluded that the "use of annotations in examples to highlight subgoals and methods seem to increase the likelihood that a learner will modify an old method rather than apply it without adaptation" (Catrambone & Holyoak, 1990, p. 600).

Across a series of subsequent studies involving a variety of transfer tasks, Catrambone (1994b, 1995a, 1995b, 1996, 1998; Catrambone & Holyoak, 1990) consistently documented that learners exposed to examples that emphasize subgoals outperformed peers presented with traditionally formatted examples. In particular, he documented the efficacy of two techniques designed to accentuate an example's discrete subgoals: labels and the visual separation of steps. Although a label may consist of a verbal specification of the subgoal to which it is attached, Catrambone (1994a, 1995b, 1996) found that it is the presence of a label, not necessarily its semantic content, that influences subgoal formation. He asserted that labels serve to chunk a set of steps together and that it is this function that encourages a learner to explain why the steps are grouped together. Moreover, Catrambone (1994b, 1995a) found that visually separating steps, by segmenting the problem's solution steps to reflect its subgoals and placing each unlabeled group of steps on separate lines, was just as effective in subgoal learning as explicitly labeling steps. In sum, Catrambone has convincingly demonstrated that structuring worked examples so they include cues designed to highlight meaningful chunks of information reflecting a problem's underlying conceptual meaning can enhance a learner's ability to learn from them and can help learners to be more successful solving novel problems.

Summary: Intra-Example Features

A number of principles can be derived from research on how to design and structure instructional examples. First, examples should be constructed to maximally integrate all sources of information—including diagrams, text, and aural presentation—into one unified presentation, since splitting students' attention across multiple, non-integrated informational sources may cause cognitive overload and impair learning. However, when an example display is complex, which occurs when an example references a complex diagram, simultaneous aural explanation must be accompanied by a method for explicitly directing students' attention to pertinent parts of the example as it is being described or discussed. Otherwise students will expend too much effort trying to locate those parts of the example that the aural presentation is referencing, which creates cognitive overload. In addition, because subgoal tasks within complex problems typically represent important conceptual ideas that students need to learn, instructional effectiveness is enhanced when examples clearly demarcate a problem's subgoal structure, either by labeling each step or by visually isolating steps in an example display.

Inter-Example Features: Lesson Design

In addition to issues regarding the design of worked examples, we must consider how the examples are sequenced and arranged during instruction. As Bruner (1966) and Glaser (1976) suggested, the sequence used in presenting instructional material is as important as the structure of that material. Research on the use of examples in lesson design has focused on several issues, including (1) the number of examples to present during instruction, (2) how and whether examples should be varied within a lesson, (3) how themes or "surface stories" might be varied to instructional advantage, and (4) how practice and examples should be intermingled.

Multiple Examples

Most educators conducting research on worked examples or, peripherally, on analogical reasoning, claim that multiple examples or analogues are necessary when students are asked to learn complex concepts during instruction (e.g., Cooper & Sweller, 1987; Gick & Holyoak, 1983; Reed, 1993; Spiro, Feltovich, Coulson, & Anderson, 1989; Sweller & Cooper, 1985). The first empirical examination of this issue, however, can be found in a study conducted by Reed and Bolstad (1991), in which the authors set out to test directly whether a single example alone can facilitate learning, or whether it is first necessary to provide at least two examples.

In an effort to address this question, Reed and Bolstad (1991) assigned college students the task of mastering word problems that involved workers operating at different rates, which required the use of the following equation: (Rate_1 x Time_1) + (Rate_2 x Time_2) = Tasks Completed. The students were assigned to one of six conditions, where the participants were presented with either (1) a simple example, which provided a basic illustration of how to employ the equation necessary for solving work problems, (2) a complex example, which made it necessary in some areas to transform the elements of the problem (rate, time, and task) before the equation could be properly employed, (3) a set of procedures, which described the fundamental steps necessary for solving work problems in general, (4) a simple example, plus procedures, (5) a complex example, plus procedures, or (6) both a simple example *and* complex example. Following instruction, the students were provided with eight test problems that differed from the simple example in terms of the number of transformations, ranging from zero to three, depending on whether any or all of the rate, time, or task elements of the problem needed to be changed before the problem could be solved using the work equation.

As Reed and Bolstad (1991) predicted, those students provided with both simple and complex examples outperformed all others on the entire posttest, including those with a single example, as well as those provided with an example plus procedures. They contended that this result indicates that two examples can facilitate learning better than a single example, even when the single example is coupled with the presentation of a set of procedures relevant to the problem at hand. In fact, the authors found that it was not necessary to provide an example for each possible test problem despite the fact that several of the test problems differed structurally from the examples in one or more ways. According to Reed and Bolstad, this implied that students were able to use information flexibly from the simple and complex examples to solve the transfer problems.

Effects of Varying Problem Types Within Lessons

How does the variability of problems within a lesson affect learning? Paas and Van Merrienboer (1994) examined this question in the context of teaching secondary technical school students problem solving in geometry. On the one hand, increasing the variability within a lesson makes sense, if acquisition of robust problem-solving schemas depends upon understanding the range of conditions under which solution procedures may be effectively applied. On the other hand, increased variability in example design may increase cognitive demand, which interferes with learning. The authors expected that problem designs that failed to limit cognitive load could yield worse performance than those that effectively limited load. Thus, the authors predicted that worked-example instruction would lead to better problem-solving performance than practice problems, a prediction consistent with the literature. They further predicted an interaction between lesson variability and type of instruction, in other words, that students using worked examples with variable problem subtypes would outperform students learning from equally variable conventional problem-solving formats, but not using worked examples.

Paas and Van Merrienboer's (1994) study utilized four groups: low-variability/practice, high-variability/practice, low-variability/example, and high-variability/example. Students in all four groups received general instruction in topics such as determining line length in two-dimensional space and plotting coordinates, given line-length. This general instruction was followed by either problem-solving practice or worked-example instruction, depending upon the group. The students studied six problems and their solutions (i.e., worked examples) in the two worked-example conditions; those in the two practice conditions were asked to solve the six problems. Those students in the two high-variability conditions received two different problem subtypes; one involved line-length determination, the other coordinate plotting. Students in the low-variability condition received only the former.

Paas and Van Merrienboer (1994) assessed the students' transfer performance for the four conditions using a six-item posttest that required students to combine various meaningful chunks (previously learned subgoals) in novel ways. They found a main effect for example-based instruction on this measure. Consistent with their prediction, they also found an interaction: Students in the worked-example condition benefited more from lesson variability than students in the practice condition. Furthermore, there was no main effect for variability, suggesting that it is not a universal good. The results of this study suggested that variability produces transfer benefits, but only in combination with instruction designed to minimize cognitive load, such as worked-example instruction.

Variability in Surface Stories

Now imagine that one wants to teach students how to discriminate between two or more types of problems and solve each correctly. Should examples be designed with surface stories that vary for similar problem types? Presumably, this would lead students to learn that surface features are not the most reliable method for categorizing problems. Or should examples rely on the same surface story within a problem type to emphasize similarity? Ross (1989) noted that "novices are likely to include superficial aspects of the task in their probes (and their memory), so both structural and superficial aspects of the task may influence what is retrieved" (p. 441). In other words, research indicates that novices tend to pay too much attention to problem context and too little attention to problems' deeper conceptual structures. Based on this research, Ross suggested that one possible way to design a lesson would be to make problems within the same type superficially similar. For example, in a lesson on proportional reasoning, all mixture type problems could be presented with examples about making lemonade, while all measurement conversion problems could be presented with examples about building a deck. Ross presumed that this superficial similarity among problems of similar structure would assist learners in categorizing the problem types and, in turn, applying the appropriate method in solving the problems. He went on to say that "as learners become more able and confident, they could be weaned away from their reliance on superficial similarities until they are able to categorize the problems by structural aspects only" (p. 464).

Quilici and Mayer (1996) investigated this approach by developing two example sets for teaching statistical concepts, one that emphasized surface features and one that emphasized structure. In the example set that emphasized surface, the *very similar* surface story was used for each problem of a given problem type; in the example that emphasized structure, a *different* surface story was used for each problem of a given problem type. According to the authors, putting emphasis on structure requires "arranging example problems so that (a) each problem type is exemplified by a battery of different cover stories that differ from one another, and (b) the same battery of cover stories is used across the problem types" (Quilici & Mayer, 1996, p. 157). Participants were randomly assigned to a structure-emphasizing example, a surface-emphasizing example, or a no-example condition. Whereas the no-example participants were not provided any instructional material, the students in the structure- and surface-emphasizing examples were asked to study material about three types of statistical problems (e.g., t test, chi-square, and correlation) that consisted of either three structure- or surface-emphasizing examples, respectively, to depict each problem type. The authors used a sort task as the dependent measure, which they found useful for evaluating the degree to which students developed organizing schemas for a set of problems. As predicted, they found that the students in the structure-emphasizing condition sorted by structure more often than their counterparts in the surface emphasizing and the no-example conditions, which did not differ significantly from each other.

In an effort to extend this finding beyond a sort task, Quilici and Mayer (1996) followed up this experiment with one that provided students with condition-appropriate material to learn just two problem types (e.g., t test and correlation). Participating students completed two sessions. In each, they studied a set of two examples and accompanying solutions, followed by two practice problems to solve. After instruction, the students were required to take a posttest consisting of four problems, two from each problem type. The participants' ability to select the correct statistical test to apply to each of the problems served as the primary dependent measure. The authors found that the participants in the structure-emphasizing condition correctly selected the appropriate test statistically more frequently than their peers in the surface-emphasizing condition. According to the authors, this result indicated that the participants exposed to the structure-emphasizing examples were less reliant on the surface features of problems and more reliant on their structural features during categorization than their counterparts who were presented with surface-emphasizing examples. Based on the findings across their experiments, Quilici and Mayer concluded that "structure-emphasizing techniques are effective because they demonstrate to students that a reliance on surface features does not work" (p. 157).

Example-Problem Pairs

In classrooms, problem-solving lessons in physics, as in other sciences and in mathematics, typically include both worked examples and practice problems for students to solve. Indeed, research suggests that some students rely heavily on examples during problem solving (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). As a result, examples and practice problems are often explicitly paired, and experimental tests have often followed this paradigm (Cooper & Sweller, 1987; Sweller & Cooper, 1985; Ward & Sweller, 1990). Following Bruner's (1966) and Glaser's (1976) call for future research on instructional sequencing, one may question this design assumption, even if it makes intuitive sense. Should examples and practice be paired?

In a recent study, Trafton and Reiser (1993) tested the pairing of examples and practice, using a set of practice and example problems created from a LISP programming curriculum. The authors designed two treatments, alternating and blocked: Participants in the alternating condition were exposed to six example-practice problem pairs, where each example was followed directly by a comparable, but not identical (i.e., each had a different cover story), practice problem (e.g., Example 1, Practice 1, Example 2, Practice 2, ... Example 6, Practice 6), whereas participants in the blocked condition were exposed to the entire set of six examples, followed by the entire set of six practice problems (e.g., Example 1, Example 2, ... Example 6, Practice 1, Practice 2, ... Practice 6). Although the items within each example-practice problem pair were similar, each of the six pairs was designed to be conceptually distinct from the rest. The authors included two dependent measures: time to solution and accuracy of solution on three near-transfer problems. Trafton and Reiser found that, as predicted, participants in the alternating-example condition took less time and produced more accurate solutions on the transfer posttest than their counterparts in the blocked-example condition. These findings were viewed as consistent with a knowledge-compilation model of learning, which suggests that examples must be available in memory during problem solving. This differs from an example-generalization model, which stipulates that problem-solving rules are acquired while studying examples. Based on these findings, the authors asserted that "the most efficient way to present material to acquire a skill is to present an example, then a similar problem to solve immediately following" (Trafton & Reiser, 1993, p. 1022).

Summary: Inter-Example Lesson Design

The conclusions from the research on inter-example variability in worked-example lesson design can be summarized briefly: First, transfer is enhanced when there are at least two examples presented for each type of problem taught. Second, varying problem sub-types within an instructional sequence is beneficial, but only if that lesson is designed using worked examples or another format that minimizes cognitive load. Third, lessons involving multiple problem types should be written so that each problem type is represented by examples with a finite set of different cover stories and that this same set of cover stories should be used across the various problem types. Finally, lessons that pair each worked example with a practice problem and intersperse examples throughout practice will produce better outcomes than lessons in which a blocked series of examples is followed by a blocked series of practice problems.

Interacting with the Learning Environment: Explanation Effects

Whereas the two previous sections dealt exclusively with factors of example and lesson design, we now examine the ways in which examples are used by the problem solver, particularly the practice of explaining examples to one's self and to others. Early research examining the effectiveness of worked examples (e.g., Sweller & Cooper, 1985; Tarmizi & Sweller, 1988) tacitly assumed that there were no individual differences in example processing style, thereby discounting the possibility that some individuals may naturally employ more or less effective methods of studying worked examples. Recently, a number of studies have found that, in fact, individuals do differ in how they approach and learn from examples (Chi, in press; Chi et al., 1989; Chi & Bassok, 1989; Chi & VanLehn, 1991; Pirolli & Recker, 1994; Renkl, 1997b; VanLehn & Jones, 1993a, 1993b).

Chi and her colleagues (Chi et al., 1989) conducted the initial, and most influential, study to date on how individuals differ in their example processing and how this ultimately affects learning. Their research examined the way in which physics-naive college students used worked examples while attempting to master an elementary physics lesson. Although students were very dependent on worked examples while studying, Chi and her colleagues noted that they often failed to fully understand the problem-solving model illustrated by the examples. As a result, students were unable to generalize from the examples to problems that differed slightly from the examples themselves (e.g., Sweller & Cooper, 1985). Chi et al. proposed that this lack of understanding on the part of some learners might stem from the incompleteness of the examples. In particular, they suggested that some students are unable to process an unexplained example effectively. Since, according to their analyses, most examples contain insufficiently explained solution steps, they suggested that the burden of explaining the rationale of poorly elaborated solution steps falls on the learner and that some learners might be better than others at providing the missing explanations. In support of this assertion, Chi and her colleagues found that learners employ qualitatively distinct strategies to offset the effect of poorly-elaborated examples. In fact, the authors noticed that, upon discovering an unexplained step, some learners temporarily suspended their examination of the example in order to generate their own justification for the actions depicted in the step. Chi and her colleagues labeled this the *self-explanation* effect. They found that the students in their study who self-explained while studying examples appeared to learn more effectively (as demonstrated by their greater success at subsequent problem solving) than those who did not exhibit this behavior.

Chi et al.'s (1989) examination of the self-explanation effect led to the discovery of rather conspicuous differences between more successful and less successful students. Based on the results from their study, Chi et al. proposed four ways in which more successful students differed from less successful students in terms of the self-explanation phenomenon. The more successful participants (1) voiced a greater number of self-explanations during example studying, including more self-explanations related to articulating the deep structure of the problem, (2) voiced more accurate self-monitoring statements during example studying, (3) were less likely to refer back to the examples while problem solving, and (4) used more focused references when they did choose to look back at the examples during problem solving.

A recent study by Renkl (1997b) examined qualitative differences among college students' self-explanation characteristics and found that learners differ substantially with respect to the quality of their self-explanations. Consistent with Chi et al.'s (1989) research, the learners' performance appeared to be directly related to the qualitative nature of their self-explanation characteristics. Renkl (1997b) discovered that the quality of the effective learners' self-explanations could be attributed to how often they attempted to self-explain the deep structure of the problems. He also found that learners showed a stable tendency in their self-explanations that was independent of the specific examples at hand. However, in a departure from Chi et al.'s (1989) initial concept of the self-explanation effect, Renkl (1997b) suggested that the overall quality of self-explanations was not dependent upon the presence of all of the various, positive aspects of self-explanation, such as accurate self-monitoring and explication of a problem's deep structure. Instead, an effective learner may consistently display only one positive self-explanation characteristic during studying, for instance, explicating a problem's deep structure, while being relatively poor on another characteristic, such as self-monitoring. Thus, a learner need not be competent in all facets of self-explanation to be successful.

In addition to his effort to examine self-explanation characteristics among learners, Renkl (1997b) also sought to identify particular self-explanation "styles" among the participants in his study based on an analysis of verbal data. Four relatively discrete self-explanation styles, two associated with successful problem solving and two associated with less success, emerged from a cluster analysis of these data. Upon closer examination, Renkl discovered that the nature of the two clusters suggested that successful students could be labeled as either *anticipative reasoners* or *principle-based explainers*. Anticipative reasoners self-explained by anticipating or predicting the next step in an example solution and then following up with a self-check in which they determined whether their predicted step matched the step displayed in the example. In contrast, those learners Renkl described as principle-based explainers sought to articulate the conceptual structure of the problem by self-explaining the problem's subgoal (conceptual) structure and explicating the domain principles on which the solutions were based. However, only a minority of students in Renkl's study showed a successful style. As a result, Renkl characterized the self-explanation style of most learners as passive or superficial, since they spent very little time studying the examples, thus missing opportunities to self-explain.

Inducing Explanations in Example-Based Instruction

The message from the self-explanation literature is clear: students who self-explain tend to outperform students who do not. Furthermore, there are different forms of self-explaining, and students often fail to self-explain successfully. Given this, a number of approaches have been proposed for encouraging learners to self-explain while processing problems. These include fostering self-explanations by structural manipulations, directly training in self-explanation, and attempting to engender self-explanation activities through social incentives. In the sections that follow, we examine each of these in turn.

Fostering Self-Explanations Through Structural Manipulations. To date, only manipulations in the intra-example features of worked examples have been associated with improvements in students' self-explanations. In particular, research has focused on three means of increasing self-explanations through structural manipulations: identifying subgoals (Catrambone, 1996, 1998), using incomplete examples (Stark, 1999), and using an integrated example format to avoid "split attention" (Mwangi & Sweller, 1998).

As previously discussed, Catrambone's research has shown that labeling subgoals in worked examples increases students' performance. With respect to self-explanations, Catrambone's subgoal learning model (1998) assumes that a label leads the learner to group a set of steps and then to try to self-explain the reason those steps go together. In the optimal case, these self-explanation attempts result in the formation of a goal that represents the purpose of the set of steps. Although his initial work found indirect support for this supposition, for instance, enhanced performance on outcome measures, in one of his more recent studies Catrambone (1996) collected more direct support for the effect of labels on self-explanations. In this work, he analyzed verbal protocol data collected while his participants studied examples, observing (a) the point at which students recognized that solution steps leading to subgoals represented a unit and (b) their explanations for what the steps accomplished, to determine whether labeling subgoals induces self-explanations. Catrambone found that subgoal labeling actually improved self-explanations and, as a consequence, transfer performance. In a recent study, Catrambone (1998) replicated these findings, thus providing clear evidence that subgoal labeling has positive effects on self-explanation.

Following Renkl's work on anticipative reasoning (1997b), Stark (1999) assumed that students who tried to anticipate problem steps would effectively self-monitor their problem solving, guarding against "illusions of understanding" that frequently occur (cf. Chi et al., 1989; Pirolli & Recker, 1994). To "force" anticipation, Stark (1999) omitted text and inserted blanks into the worked examples of Renkl (1997b). The learners' task was to try to name what was missing. After attempting to fill in the blanks, the students received feedback on the correctness of their responses. Stark found that compared to studying complete examples, incomplete examples fostered explanations and reduced ineffective self-explanations, such as rereading or paraphrasing. As a consequence, incomplete examples enhanced the transfer of learned solution methods. This result contrasts with observations by Paas (1992), who found no differences between incomplete and complete examples. However, the main purpose of Paas's study was not to investigate the effects of complete versus incomplete examples.

Several studies by Sweller and colleagues have shown, as noted, that integrated examples are more effective than examples in which the learner's attention must be directed to different information sources (split-source format). Mwangi and Sweller (1998) sought to determine whether the advantage of an integrated format is mediated by the quality of explanations. In two experiments they analyzed student explanations as a function of integrated versus split-source format. Students were instructed to pretend that they were explaining the examples to another student. It is important to note, however, that, compared to most other studies that have examined this issue, Mwangi and Sweller employed a different conception of self-explanations. Their study assessed self-explanations by having learners explain example solutions to an imaginary student after initial example learning. Hence, this procedure did not afford study of spontaneous or concurrent self-explanations, but rather induced students to make pretend explanations for somebody else. With this restriction in mind, Mwangi and Sweller found that student explanations were different depending on whether the student used a split-format or integrated example. For instance, students had greater difficulty understanding split-source examples, and more often simply re-read them. When students did reread integrated examples, they tended to be more focused and more often linked the process to justifying specific solution steps.

Training Self-Explanations. Since the publication of Chi et al.'s (1989) results on the importance of self-explanations, several studies have been conducted in which students were trained in self-explaining. For example, Chi, DeLeeuw, Chiu, and LaVancher (1994) prompted self-explanations of learners reading a text on the circulatory system. Even without extensive self-explanation training, students in the Chi et al. study who were prompted to self-explain while reading the text achieved a deeper level of understanding of the circulatory system—as assessed by a variety of measures, including the accuracy of their mental models—than their peers who were not prompted to self-explain. Neuman and Schwarz (1998) trained students in self-explanations in the context of problem solving. Although both studies successfully induced self-explanations, they are not discussed here because they did not investigate learning from worked examples.

More important in this context is the study of Bielaczyc, Pirolli, and Brown (1995), since worked examples were a significant part of their learning materials (text and examples on LISP programming). In an experimental group, participants were explicitly trained in self-explaining. The training consisted of (a) introducing and motivating self-explanations, (b) learning from a student model on videotape, and (c) verifying the participants' ability to provide elaborated self-explanations (Bielaczyc et al., 1995, p. 231). The control group learners also received some training, such as the viewing of a student model, but this intervention was more implicit—it did not, for instance, incorporate explicit training in the application of self-explanation strategies. The explicit training was substantially more effective than the implicit training in fostering self-explanations in students' studying examples and text. Consequently, the learning outcomes (programming performance) were superior in the explicit-training group.

Two other studies on training students to self-explain provide data directly related to learning from examples. Nathan, Mertz, and Ryan (1994) trained learners to provide self-explanations while studying worked examples and while solving corresponding problems. Although the details of the training were not provided, the authors found that training self-explanations fostered learning when an algebra story problem was studied, but not when an algebra manipulation problem (solving for the unknown variable) was presented. Nathan et al. concluded that self-explanations are effective when conceptually oriented examples are studied, if the examples illustrate domain principles. When worked example instruction focuses primarily on procedures, learners have little to elaborate. Thus, training students to elaborate under such conditions makes little sense.

Finally, a study by Renkl, Stark, Gruber, and Mandl (1998) provides empirical evidence of the trainability of self-explanations. The authors conducted an experiment to test the effect of short self-explanation training, with special emphasis on explicating goal-operator combinations, that is, explaining what goals need to be met in problem solving and what actions are needed to reach them. For learning materials, Renkl et al. used examples from the domain of compound interest and real interest calculation. Half of the learners received a short training session of about 15 minutes that included the following components: (a) information on the importance of self-explanations, (b) modeling self-explanations (one worked example), and (c) coached practice (another worked example). Participants in the alternate condition received thinking-aloud training. After these interventions, all participants independently learned from worked examples. The explicit-training intervention had a very strong effect on self-explanation activities (effect size of about two standard deviations), and learning outcomes (assessed by performance on transfer problems) also reliably improved. In the case of near transfer, Renkl et al. (1998) found an aptitude-treatment interaction, where learners with low prior topic knowledge tended to profit most from the training.

Use of Social Incentives. The results of the Renkl (1997b) study suggest that most learners are passive or superficial self-explainers. One possible way to change this situation is to assign a student to the role of explainer in cooperative learning settings. Following this idea, Renkl (1995, 1997d) investigated whether assigning students to the role of "teacher" fostered self-explanation activities and learning outcomes. He predicted that a teaching expectancy motivates learners to thoroughly self-explain the worked examples in order to prepare themselves for the later teaching demand. The learners in an experimental group were told to study worked examples so they could later explain the solution rationale of similar examples to a co-learner. The participants in a control group were told that they would have to work similar problems after studying the examples. Prior to any teaching activity by the students and using test problems of different transfer distance to the worked examples presented, Renkl immediately assessed learning outcomes to determine the instructional value of the experimental group's preparation for teaching. The results of this experiment were surprising, as the teaching expectancy did not significantly improve performance but instead appeared to hamper learning, partly because of increased stress and reduced intrinsic motivation on the part of the students.

Renkl (1996, 1997a, 1997d) then studied the effects of generating explanations for someone else. For this purpose, he formed yoked pairs of participants. After a preparatory individual learning phase, one partner (experimental group) explained the solution rationale of examples to his or her partner (control group). Again, the results were counter-intuitive. The demand to explain for a co-learner actually increased explanation activities, but did not lead to better learning results. Instead, the listeners tended to outperform the explainers. Post-hoc analyses indicated that learners with little prior experience with tutoring tended to perform poorly when cast in the role of teacher, while participants with some tutoring experience learned as much as the listeners.

In the final set of studies in this program, Renkl (1997c, 1997d, 1998) investigated the effects of sophisticated co-learner questions on explaining and learning. Renkl assumed that responding to questions would foster the learners' construction of conceptual understandings of the problem and thereby enhance transfer. To test this assumption, the participants in an experimental group explained the solution rationale of worked examples to a putative co-learner (confederate), who asked "what if" questions. In the control group, the confederate was more or less totally passive. Renkl found that the co-learner questions fostered one type of explanations (elaborating the situation), but all other types of explanations, principle-based explanations, for instance, were reduced. As a consequence, the intervention appeared to impede intrinsically motivated learners, perhaps because the co-learner questions hampered their sophisticated spontaneous explanation activities. However, the outcomes for learners with low intrinsic motivation, whose spontaneous explanation activities were very poor, improved. Overall, Renkl found that co-learner questions raised the quality of poorly motivated students' explanation activities to average levels.

In sum, attempting to foster explanations through teaching appears to yield disappointing results. These results are mirrored by a recent study conducted by Mwangi and Sweller (1998), who also found that outcomes did not improve for learners instructed to pretend that they were explaining examples to another person. However, given the empirical evidence on the positive effects of explaining in cooperative arrangements (e.g., Webb, 1991), we should not conclude that explaining to others does not help when studying worked examples. Additional analyses of Renkl's data (Renkl, 1997d) suggest that there were at least two factors that moderated the effects of learning by teaching: prior tutoring experience and prior content knowledge. Learners who are not familiar with the role of an explainer (tutor) and for whom the learning materials are difficult (those with low prior knowledge) are overwhelmed and stressed by the dual task of teaching and learning. Unfortunately, we currently lack detailed knowledge on factors that moderate the effectiveness of learning by teaching.

Summary: Explanation Effects With Worked Examples

In conclusion, research on explanation effects suggests that self-explanations are an important learning activity during the study of worked examples. Unfortunately, the present research suggests that most learners self-explain in a passive or superficial way. Among the successful learners, there seem to be different subgroups employing different self-explanations styles (anticipative reasoning and principle-based explanations). Both of these styles can be fostered by instructional methods. Direct training appears to be effective, as are structural manipulations of examples such as adding subgoal labels, utilizing an integrated format, or using "incomplete" examples. Less promising are the data on improving self-explaining (and problem solving) through setting social incentives to explain, such as inducing students to prepare to tutor others. In particular, students who have no prior tutoring experience and who are novices within the domain being tutored appear to experience stress and overload when asked to provide instructional explanations.

Worked Examples Research: Synthesis and Commentary on Future Research

A Model for Instructional Design

Early in this review we acknowledged that classrooms are situated within social and cultural contexts that significantly shape the learning that occurs within them. Nevertheless, we argued for the importance and relevance of experimental findings, citing a substantial body of evidence that many successful and thriving programs of classroom reform have built upon controlled research grounded in cognitive science. The worked examples research reviewed, conducted in both classrooms and in "laboratories" that simulated classroom instruction in relevant ways, represents an important example of a cognitively-based educational research program that is relevant to practice in the sense argued by John Bruer (1993). In confining our review to studies that met credibility standards for controlled, experimental research, we were able to draw relatively strong inferences about important causal factors that are likely to mediate the effectiveness of instructional examples used in actual classroom settings.

Our review was organized to emphasize a particular perspective regarding three major categories of factors that influence learning from worked examples. These categories of influence lead to principles and recommendations concerning (1) how examples should be constructed, (2) how lessons that include examples should be designed, (3) how the thinking processes that students use when studying examples can be fostered. We now propose a framework, shown as Figure 2, for discussing what appear to be the important causal interrelationships among these categories

As depicted in Figure 2, we postulate that learning from worked examples causes learners to develop knowledge structures representing important, early foundations for understanding and using the domain ideas that are illustrated and emphasized by the instructional examples provided. These representations guide problem solving and they may be conceptualized as representing early stages in domain schema development and in the acquisition of expertise in accordance with Anderson's model of skills acquisition (e.g., Anderson et al., 1997). Through use and practice, these representations are expected to evolve over time to produce the more sophisticated forms of knowledge that experts use. Even after expertise is achieved, learners can benefit from study of examples representing the performance of other experts.

The outcomes of example-based learning and their functionality are influenced by the several sets of factors represented in Figure 2. One set of factors pertains to the manner in which an example-based lesson is put together, and the influence of these factors on learning outcomes is indicated in Figure 2 by the arrow connecting box I (Lesson and Example Design) to box III (Learning Outcomes).

As indicated in box I, designers of example-based instruction must decide, among other issues, how many examples to provide for each type of problem presented. The number of examples that can be used for teaching a particular idea may be constrained in practice by such issues as instructional time and problem complexity, since teachers often cannot present many complex examples. Research by Reed and Bolstad (1991) indicates that one example may be insufficient for helping a student induce a usable idea and that the incorporation of a second example illustrating the idea, especially one that is more complex than the first, garners significant benefits for transfer performance. So, "at least add a second example" appears to be a basic rule for worked-examples instructional design.

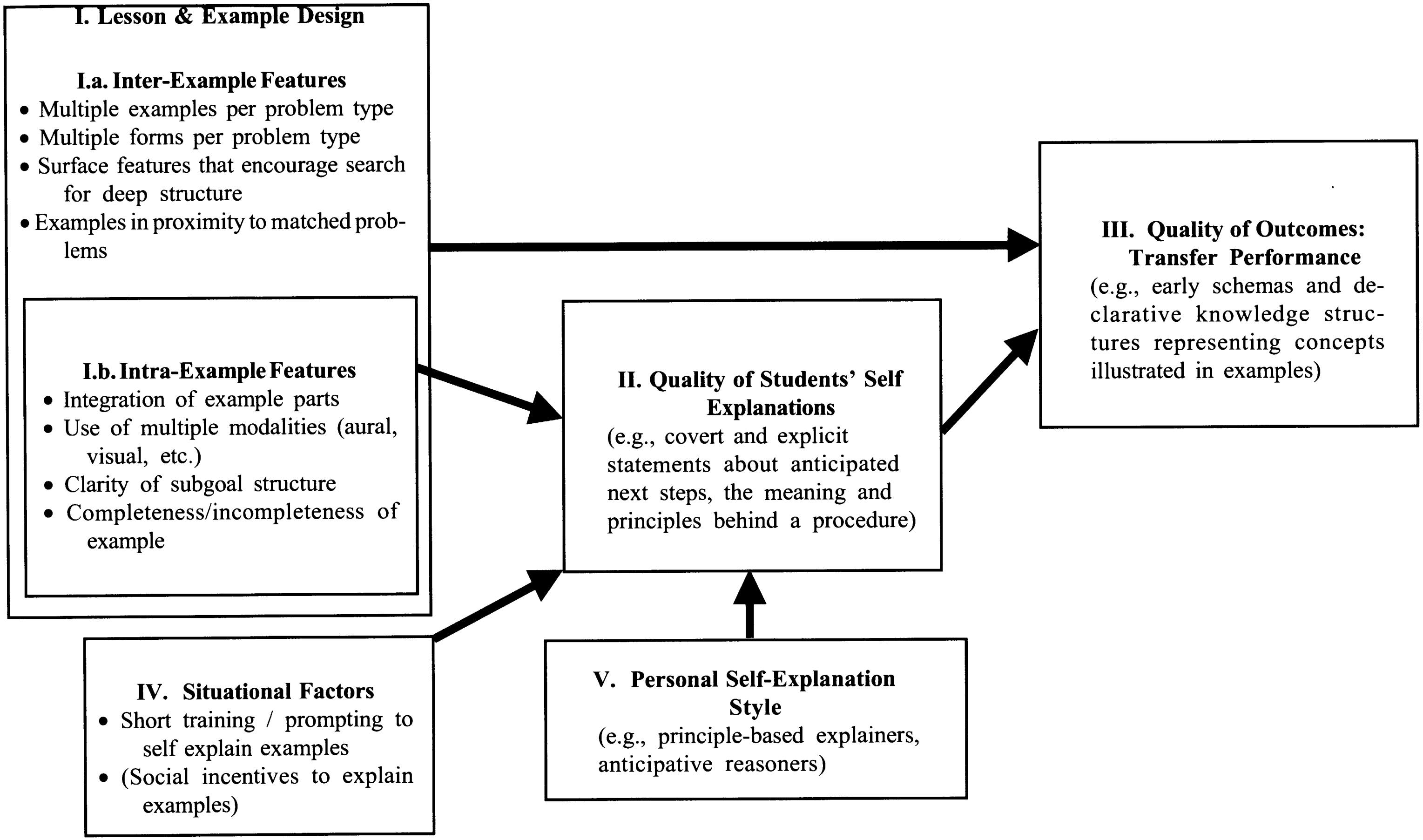

Figure 2. *Framework for discussing the causal interrelations among three major categoreis of factors influencing the learning from worked examples*

Other lesson-design factors also included in Figure 2 are the variability in the types of problems used in a lesson, how to use surface features strategically to emphasize deeper conceptual structure and how to intersperse and coordinate examples with actual problem solving. Worked-examples lessons will promote transfer if they include variability. This means that examples within lessons should differ from each other in terms of their numerical values *and* form, as opposed merely to their numerical values (Paas & Van Merrienboer, 1994). However, if a teacher wants beginning students to notice that different structural characteristics are associated with different problem types, these characteristics can profitably be emphasized in the beginning by manipulating formats, such as cover stories, across examples and between problem types (Quilici & Mayer, 1996). In this case, similar problem types should all have different cover stories since, according to Qulici and Mayer (1996), "when students see the same battery of cover stories used across problem types, they are more likely to notice that surface features are insufficient to distinguish among problem types" (p. 157). However, regardless of the number of problem types covered, the most effective way of structuring a worked example lesson is to link each example explicitly to its target practice problem (Trafton & Reiser, 1993), rather than to present a block of different examples followed by massed practice in problem solving.

As indicated by box I.b of Figure 2, we also found that the structure or design of the worked examples within lessons plays a critical role in learning. When examples require students to reference and integrate multiple sources of information, cognitive overload can occur. Sweller and his colleagues (Mousavi et al., 1995; Tarmizi & Sweller, 1988; Ward & Sweller, 1990) call this the split-attention effect and offer two suggestions for combating it. First, ensure that examples are formatted so that information within the examples is physically integrated. Next, whenever possible, simultaneously supplement examples with aural explanations, particularly when providing information about an example diagram. When example diagrams are complex, a method must be found to direct students' attention to pertinent parts of the diagram as the aural information is presented. Finally, Catrambone's research (1994a, 1994b, 1995a, 1995b, 1996; Catrambone & Holyoak, 1990) indicates that worked examples should be structured so that subgoals are emphasized by visually isolating them, by labeling them, or both.

As indicated by the arrow from box I.b to box II in Figure 2, there is evidence that the structure of worked examples enhances students' self-explanation behavior. Moreover, there is evidence that students' self-explanation behavior during study in turn mediates learning, as indicated by the arrow from box II to box III. However, it has not been determined that the effects of example structure on learning outcomes are fully mediated by self explanation. Hence, our model also includes a direct arrow from the lesson and example features box (box I) to the learning outcomes of box III. There is, of course, a strong possibility that other, up to now unidentified mechanisms, are involved in mediating the effects of example structure.

The research, and consequently the framework, also suggests that in addition to example structure, situational factors, such as training and social incentives, can foster self-explanations. Several studies have shown that self-explanations can be influenced favorably by short training sessions. Since it is unrealistic to assume that short interventions have enduring effects on individuals' explanation styles, short training sessions are viewed as situational factors that affect immediate learning activities, but not stable personal characteristics. Unfortunately, there is presently no self-explanation training designed to change personal styles. Social incentives, such as preparing an explanation to tutor a partner, are also considered situational factors that can engender self-explanation. However, they do not necessarily enhance learning outcomes, as a number of studies have shown. Hence, Figure 2 places the phrase "social incentives" in parentheses, indicating that further clarification is needed to determine which social incentives lead to favorable outcomes and under what conditions. Given findings from the worked examples literature that seem to contradict evidence from the cooperative learning literature regarding the positive effects of being an explainer, our principle here is unclear.

The arrow drawn from box V to box II in Figure 2 represents the finding that the number and quality of self-explanations associated with the personal self-explanation style used by an individual while studying worked examples is known to influence learning outcomes. Renkl (1997b) has shown that it is reasonable to attribute specific self-explanation styles to individual learners. This means that a person's actual self-explanations depend, among other things, on his or her stable tendency to provide specific explanations.

The model depicted in Figure 2 provides a useful framework for thinking about worked-example design and for planning future research on basic cognitive mechanisms and instructional interventions. For instance, the model does not contain a link between inter-example features and quality of students' self-explanations. This suggests that research has not yet uncovered the relationship between quality of students' self-explanations and inter-example lesson features, although it might in the future. Moreover, the model implies that a number of other unanswered questions remain, including (1) What are the specific mechanisms that mediate the effects of lesson- and example-design features on learning outcomes, (2) Are there mediating mechanisms other than self-explanations that are responsible for the learning effects associated with the processing of worked examples, (3) By which kind of training can personal self-explanation styles be most effectively changed, and (4) Are there circumstances under which certain types of social incentives can be used to foster self-explanations and, in turn, learning outcomes?

Implications and New Directions

To the extent that worked examples research has produced general principles about how students learn through study of examples and related problem solving, the findings of this program may have implications for design of constructivist learning environments in which students learn by solving complex problems (e.g., Williams & Hmelo, 1998). For example, with the Problem-Based Learning (PBL) instructional paradigm (e.g., Wilkerson & Gijselaers, 1996), students learn subject matter as it is needed for solving real-world problems. PBL problems are typically ill structured and complex, designed to mimic professional practice and other real-life problem situations. Problems are often presented to students as cases, such as medical cases, and students are guided by a tutor as they analyze cases and seek solutions, for example, diagnoses and treatments. Sometimes expert or student solutions to the same or similar problems are made available to students, either before, during, or after solving.

The PBL approach is increasingly popular and frequently used in both professional and K-16 education (Williams, 1992; Williams & Hmelo, 1998). Leading teachers and educational researchers advocate PBL as a method for helping students acquire *useful knowledge* that will transfer into working and other real-world contexts. Yet, PBL can be complex, difficult and time-consuming for both students and teachers (e.g., Derry, Levin, Osana, Jones, & Peterson, in submission). Principles derived from the worked-examples literature might be applied to help improve PBL instructional design. The efficacy of those principles for PBL could be evaluated through experimental research.

For example, the Secondary Teacher Education Project (STEP) (http//:www.wcer.wisc.edu/step) is a web-based instructional program under development that employs video cases of real classroom practice to help secondary education majors learn to reason about instructional design. Groups of students are asked to study actual classroom cases and propose redesign solutions that use concepts from a course in instructional psychology. Each case is linked to one or more web pages discussing specific course concepts. Each case is also associated with one or more expert analyses. How should these resources be organized and used to produce the most effective instruction?

The worked-examples literature suggests that students should study expert case solutions before attempting similar case-redesign problems of their own. Also, most guidelines derived from the worked-examples literature and shown in Figure 2 can be applied to the PBL instructional model, as exemplified in STEP, with only small translation. Our illustration follows.

Inter-Example Lesson Features

Examples in proximity to matched problems. Each expert solution should be matched with similar case-based problems for students to solve; matched problems should be presented in close proximity to their matched expert solutions. In STEP, for example, if the student's task is to design an inquiry approach to teaching a science concept, this problem could be immediately preceded by an expert example of an inquiry approach to teaching a similar science concept.

Multiple examples per problem type. Students should experience a variety of different problem cases and example solutions for each to-be-learned concept. For example, *instructional scaffolding* is a to-be-learned concept within STEP, and so a variety of classroom learning problems in which scaffolding is part of the solution, and a variety of different approaches to providing instructional scaffolding, (for instance., through course structure, personal mentoring, etc.), are given.

Surface features that encourage search for deep structure. Students should examine each problem case from very different conceptual perspectives, solving the same problem using multiple solutions and different points of view. For example, in STEP, the same classroom case can legitimately be viewed as a problem of providing too little instructional scaffolding or, alternatively, as a problem of failing to gain and focus students' attention.

Intra-Example Features

Integrating example parts. To avoid split-attention effects in study of expert analyses, present case videos and expert case analyses in a single integrated package. In STEP, for instance, expert case analyses that were once presented as separate text that students could read after watching a video are now being redesigned as dynamic narratives incorporated directly into video cases.

Use of multiple modalities. Present expert case analyses using simultaneous multiple modalities, such as aural explanation overlaid on video.

Clarity of subgoal structure. The expert case analysis should explicitly label, segregate, or otherwise specify the individual concepts underlying the case. For example, as an expert discusses concepts such as *scaffolding* or *attention* in reference to a classroom video, the presentation must be designed to signal clearly, perhaps using arrows or other symbols, which specific actions within the video match the target concepts being discussed.

Completeness/incompleteness of example. Incomplete expert case analyses may be preferable because they require students to make inferences and fill in gaps, fostering self-explanation during study. In STEP, for example, students are sometimes asked to complete or adapt unfinished expert solutions to classroom problems.

Situational Factors

Social incentives to explain examples. Asking students to prepare case analyses for the purpose of instructing others will not foster productive self-explanation behavior during study of worked examples. However, group discussions of expert analyses may help foster self-explanatory processing and hence improve learning. Accordingly, the STEP program has adopted a small-group case discussion format.

Short training/prompting to self explain examples. Training and prompting students to self-explain during study of expert analyses and problem solving will improve transfer learning. In STEP, for example, self-explanation behavior is modeled and encouraged by trained small-group facilitators.

The example above illustrates how principles derived from the worked examples literature are supporting design and study of a complex form of problem-based learning in one instructional research project.

Concluding Comments

Educational researchers today are asking how to create and study authentic learning environments, classroom communities that employ complex, real-world problems as instructional contexts. Well-known modern approaches to authentic instruction in classrooms include anchored instruction, apprenticeship models, case-based instruction, and problem-based learning, among others (e.g., Williams, 1992). Because the worked examples research has been conducted largely in controlled settings with relatively simple problems, it would be easy for researchers who support authentic instructional paradigms to overlook or ignore findings from this literature. Yet the worked examples research is one of several strong cognitive-theoretical programs of experimental study yielding principles of potentially great importance for helping educators foster learning through problem solving and study of examples of good problem solving. Whether or not the application of these principles can significantly enhance student learning in authentic problem-solving contexts, as it has in laboratory ones, is a question that worked examples researchers should now attempt to answer in partnership with classroom researchers and practitioners.

The current focus on crafting and sustaining authentic learning environments evolved, in part, as a result of a common goal, shared by many educators, of promoting students' abilities to engage in adaptive, flexible transfer. Critics of worked examples instruction may raise the issue that worked examples are unable to assist classroom communities in achieving this goal since their effectiveness is limited to training students to use a particular procedure under narrowly defined conditions. As a result, critics may claim that students exposed to worked examples are not able to solve problems with solutions that deviate from those illustrated in the examples, can not clearly recognize appropriate instances in which procedures can be applied, and have difficulty solving problems for which they have no worked examples. These limitations, critics might argue, call into question whether examples are appropriate for classroom instruction since they do not promote anything beyond superficial learning to imitate procedures, which is exactly the type of learning that precludes flexible adaptation to novel problems and contexts.

The current review suggests, however, that examples can in fact help educators achieve the goal of fostering adaptive, flexible transfer among learners. For instance, the research on inter-example features of lesson design point to the importance of providing a wide range of examples (and having students emulate examples) that illustrate multiple strategies and approaches to similar problems, which should help foster broad transfer and "cognitive flexibility" (Spiro, Feltovich, Jacobson, & Coulson, 1991). In addition, the lesson design strategies discussed in this review have tremendous potential to make expert thinking, not just procedures, visible and accessible to students, expert thinking that illustrates and makes visible flexible, creative problem solving and appropriate beliefs about mathematics as well as metacognitive monitoring. To achieve this goal, it is possible to structure an example within a computer-based multimedia environment to illustrate mathematics as a thinking process by depicting an expert thinking aloud as he/she endeavors to solve the problem at hand. This type of example would resemble Schoenfeld's (1987) suggested method of teaching mathematics, in which the instruction illustrates mathematical problem solving as thinking and struggling, not simply as a "neat" procedural process. A prototype of this example is currently being used in a computer-based instructional environment called Tutorials in Problem Solving (TiPS). TiPS incorporates a graphic problem-solving interface and dynamically-represented worked examples that include both aural and visual modeling of expert problem solving processes. These features are designed to help promote students' abilities to model and reason flexibly about a wide variety of story problems (Derry, Wortham, Webb, & Jiang, 1996; Derry et al., 1994; *http://www.wcer/wisc/edu/tips/*). Thus, one way in which example-based instruction has the potential to overcome the perception that they provide exceedingly procedurally oriented instruction is by illustrating an expert's underlying thinking process as she or he engage in problem solving.

This review also provides some empirical evidence that calls into question each of the specific limitations about example-based instruction that might be raised by critics. As noted earlier, Catrambone and Holyoak's (1990) research documented that learners are capable of solving problems whose procedures deviate from those illustrated in the worked examples. According to research conducted by Quilici and Mayer (1996), learners can recognize appropriate instances when procedures depicted in examples should be applied. Finally, the results of Reed and Bolstad's (1991) study suggest that learners are proficient at solving problems for which they are not provided worked examples. In sum, the current review suggests that worked examples, at least on a fundamental level, promote the type of flexible transfer that educators are seeking in their classroom.

Much work remains to be done, particularly as the new instructional paradigms develop further and as new computer and video technologies enhance our capabilities for dynamically representing realistic problem situations and their underlying concepts in computer-based worked examples using visualization and modeling. We expect that, as researchers develop new problem forms and worked examples, the questions addressed in this review will be modified as follows: How can examples of authentic problem solving be designed to reduce cognitive load and promote acquisition of transferable cognitive structures? When and how should authentic examples be introduced into learning community activities? How can we design classroom discourse and direct instruction to engender productive self-explaining of examples by learners? Our review already points to some possible answers.

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References

Anderson, J. R., Fincham, J. M., & Douglass, S. (1997). The role of examples and rules in the acquisition of a cognitive skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 932-945.

Bielaczyc, K., Pirolli, P. L., & Brown, A. L. (1995). Training in self-explanation and self-regulation strategies: Investigating the effects of knowledge acquisition activities on problem solving. *Cognition and Instruction, 13,* 221-252.

Bourne, L. E., Goldstein, S., & Link, W. E. (1964). Concept learning as a function of availability of previously learned information. *Journal of Experimental Psychology, 67,* 439-448.

Bruer, J. T. (1993). *Schools for thought: A science of learning in the classroom.* Cambridge: MIT Press.

Brewer, W. F., & Nakamura, G. V. (1984). The nature and function of schemas. In R. S. Wyer & T. K. Srull (Eds.), *Handbook of Social Cognition* (pp. 119-160). Hillsdale, NJ: Erlbaum.

Bruner, J.S. (1966). *Toward a theory of instruction.* New York: W.W. Norton

Bruner, J. S., Goodnow, J., & Austin, G. (1956). *A study of thinking.* New York: Wiley.

Carroll, W. M. (1994). Using worked examples as an instructional support in the algebra classroom. *Journal of Educational Psychology, 86,* 360-367.

Catrambone, R. (1994a). The effects of labels in example on problem solving transfer. In A. Ram, & K. Eiselt (Eds.), *Proceedings of the Sixteenth Annual Conference of the Cognitive Science Society* (pp. 159-164). Hillsdale, NJ: Erlbaum.

Catrambone, R. (1994b). Improving examples to improve transfer to novel problems. *Memory & Cognition, 22,* 606-615.

Catrambone, R. (1995a). Aiding subgoal learning: Effects on transfer. *Journal of Educational Psychology, 87,* 5-17.

Catrambone, R. (1995b). Effects of background on subgoal learning. In J. D. Moore & J. F. Lehman (Eds.), *Proceedings of the Seventeenth Annual Conference of the Cognitive Science Society* (pp. 259-264). Hillsdale, NJ: Erlbaum.

Catrambone, R. (1996). Generalizing solution procedures learned from examples. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 1020-1031.

Catrambone, R. (1998). The subgoal learning model: Creating better examples so that students can solve novel problems. *Journal of Experimental Psychology: General, 127,* 355-376.

Catrambone, R., & Holyoak, K. J. (1990). Learning and subgoals and methods for solving probability problems. *Memory & Cognition, 18,* 593-603.

Chase, W. G., & Simon, H. A. (1973). The mind's eye in chess. In. W. G. Chase (Ed.), *Visual information processing*. New York: Academic Press.

Chi, M. T. (in press). Self-explaining: The dual process of generating inferences and repairing mental models. In G. R. (Ed.), *Advances in instructional psychology*. Mahwah, NJ: Erlbaum.

Chi, M. T., & Bassok, M. (1989). Learning from examples via self-explanation. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 251-282). Hillsdale, NJ: Erlbaum.

Chi, M. T., Bassok, M., Lewis, M. W., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science, 13,* 145-182.

Chi, M. T., de Leeuw, N., Chiu, M. H., & La Vancher (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18,* 439-477.

Chi, M. T., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121-152.

Chi, M. T., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence* (pp. 7-75). Hillsdale, NJ: Erlbaum.

Chi, M. T., & VanLehn, K. A. (1991). The content of physics self-explanations. *Journal of the Learning Sciences, 1,* 69-106.

Cooper, G., & Sweller, J. (1987). Effects of schema acquisition and rule automation on mathematical problem-solving transfer. *Journal of Educational Psychology, 79,* 347-362.

Derry, S. J., Wortham, D., Webb, D., & Jiang, N. (1996, April). *Tutorials in problem solving (TiPS).: Toward a schema-based approach to instructional tool design.* Paper presented at the annual meeting of the American Educational Research Association, New York, NY.

Derry, S. J., Tookey, K., Smith, C., Potts, M. K., Wortham, D., W., & Michailidi, A. (1994). *Psychological foundations of the TiPS system: A handbook for system 1.0 (Technical Report).* Madison, WI: Wisconsin Center for Education Research.

Derry, S. J., Levin, J. R., Osana, H. P., Jones, M. S. & Peterson, M. (in submission). Fostering students' statistical and scientific thinking: Lessons learned from an innovative college course.

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15,* 1-38.

Glaser, R. (1976). Components of a psychology of instruction: Toward a science of design. *Review of Educational Research, 46,*1-24.

Hinsley, D. A., Hayes, J. R., & Simon, H. A. (1977). From words to equations meaning and representation in algebra word problems. In M. A. Just & P. A. Carpenter (Eds.), *Cognitive Processes in Comprehension* (pp. 89-106). Hillsdale, NJ: Erlbaum.

Jeung, H., Chandler, P., & Sweller, J. (1997). The role of visual indicators in dual sensory mode instruction. *Educational Psychology, 17,* 329-433.

Mawer, R., & Sweller, J. (1982). The effects of subgoal density and location during problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8,* 252-259.

Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? *Educational Psychologist, 32,* 1-19.

Mayer, R. E., Moreno, R., Boire, M., & Vagge, S. (1999). Maximizing constructivist learning from multimedia communications by minimizing cognitive load. *Journal of Educational Psychology, 91*, 638-643.

McGilly, K. (Ed.) (1998). *Classroom lessons: Integrating cognitive theory and classroom practice.* Cambridge, MA: The MIT Press.

Mousavi, S. Y., Low, R., & Sweller, J. (1995). Reducing cognitive load by mixing auditory and visual presentation modes. *Journal of Educational Psychology, 87,* 319-334.

Mwangi, W., & Sweller, J. (1998). Learning to solve compare word problems: The effect of example format and generating self-explanations. *Cognition and Instruction, 16,* 173-199.

Nathan, M. J., Mertz, K.,& Ryan, R. (1994). *Learning though self-explanations of mathematics examples: Effects of cognitive load.* Paper presented at the Annual Meeting of the American Educational Research Association, New Orleans.

Neuman, Y., & Schwarz, B. (1998). Is self-explanation while solving problems helpful? The case of analogical problem solving. *British Journal of Educational Psychology, 68,* 15-24.

Owen, E., & Sweller, J. (1985). What do students learn while solving mathematics problems? *Journal of Educational Psychology, 77,* 272-274.

Paas, F. (1992). Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive load approach. *Journal of Educational Psychology, 84,* 429-434.

Paas, F., & Van Merrienboer, J. (1994). Variability of worked examples and transfer of geometrical problem-solving skills: A cognitive-load approach. *Journal of Educational Psychology, 86,* 122-133.

Palincsar, A. S., & Brown, L. R. (1984). Reciprocal teaching and comprehension-fostering and monitoring activities. *Cognition and Instruction, 1,* 117-175.

Pirolli, P., & Recker, M. (1994). Learning strategies and transfer in the domain of programming. *Cognition and Instruction, 12,* 235-275.

Quilici, J. L., & Mayer, R. E. (1996). Role of examples in how students learn to categorize statistics word problems. *Journal of Educational Psychology, 88,* 144-161.

Reed, S. K. (1993). A schema-based theory of transfer. In D. K. Detterman, & R. J. Sternberg (Eds.), *Transfer on trial: Intelligence, cognition, and instruction* (pp. 39-67). Norwood, New Jersey: Ablex.

Reed, S. K., & Bolstad, C. A. (1991). Use of examples and procedures in problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 753-766.

Renkl, A. (1995). Learning for later teaching: An exploration of mediational links between teaching expectancy and learning results. *Learning and Instruction, 5,* 21-36.

Renkl, A. (1996). Lernen durch ErklärenCoder besser doch durch Zuhören? [Learning by explaining, or better, by listening?]. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie, 28,* 148-168.

Renkl, A. (1997a, March). *Learning by explaining, or better, by listening?* Paper presented at the „Annual Meeting of the American Educational Research Association“ in Chicago.

Renkl, A. (1997b). Learning from worked-out examples: A study on individual differences. *Cognitive Science, 21,* 1-29.

Renkl, A. (1997c). Lernen durch Erklären: Was, wenn Rückfragen gestellt werden? [Learning by explaining: What if questions were asked?]. *Zeitschrift für Pädagogische Psychologie, 11,* 41-51.

Renkl, A. (1997d). *Lernen durch Lehren. Zentrale Wirkmechanismen beim kooperativen Lernen* [Learning by teaching. Central mechanisms of cooperative learning]. Wiesbaden: DUV.

Renkl, A. (1998, April). *Learning by explaining in cooperative arrangements: What if questions were asked?* Paper presented at the „Annual Meeting of the American Educational Research Association“ in San Diego.

Renkl, A., Atkinson, R. K., & Maier, U. H. (2000). *From example study to problem solving: Smooth transitions help learning* (Institute of Psychology Research Report No. 140). Freiberg, Germany: University of Freiberg.

Renkl, A., Stark, R., Gruber, H., & Mandl, H. (1998). Learning from worked-out examples: The effects of example variability and elicited self-explanations. *Contemporary Educational Psychology, 23,* 90-108.

Ross, B. H. (1989). Remindings in learning and instruction. In S. Vosnaiadou & A. Rotony (Eds.), *Similarity and Analogical Reasoning* (pp. 438-469). Cambridge, MA: Cambridge University Press.

Rumelhart, D. E., & Ortony, A. (1977). The representation of knowledge in memory. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge.* Hillsdale, NJ: Erlbaum.

Schoenfeld, A. (1987). What's all the fuss about metacognition? In A. Schoenfeld (Ed.), *Cognitive science and mathematics education* (pp. 189-216). Mahwah, NJ: Erlbaum.

Scribner, S. (1984). Studying working intelligence. In M. Rogoff & J. Lave (Eds.), *Everyday cognition: Its development in social context.* (pp. 9-28). Cambridge, MA: Harvard University Press.

Shuell, T. J. (1996). The role of educational psychology in the preparation of teachers. *Educational Psychologist, 31*, 5-14.

Silver, E. A. (1979). Student perceptions of relatedness among mathematical verbal problems. *Journal for Research in Mathematics Education, 10,* 195-210.

Silver, E. A., & Marshall, S. P. (1990). Mathematical and scientific problem solving: Findings, issues and instructional implications. In B. F. Jones & C. Idol (Eds.), *Dimensions of thinking and cognitive instruction*, Hillsdale, NJ: Erlbaum.

Spiro, R. J., Feltovich, P. J., Coulson, R. L., & Anderson, D. K. (1989). Multiple analogies for complex concepts: Antidotes for analogy-induced misconceptions in advanced knowledge acquisition. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 498-531). New York: Cambridge University Press.

Spiro, R. J., Feltovich, P. J., Jacobson, M., & Coulson, R. L. (1991). Cogntive flexibility, constructivism and hypertext: Advanced knowledge acquisition in ill-structured domains. *Educational Technology, 31,* 24-33.

Stark, R. (1999). *Lernen mit Lösungsbeispielen. Der Einfluß unvollständiger Lösungsschritte auf Beispielelaboration, Motivation und Lernerfolg* [Learning by worked-out examples. The impact of incomplete solution steps on example elaboration, motivation, and learning outcomes]. Bern, CH: Huber.

Sweller, J., & Cooper, G. A. (1985). The use of worked examples as a substitute for problem solving in learning algebra. *Cognition and Instruction, 2,* 59-89.

Sweller, J. & Levine, M. (1982). Effects of goal specificity on means-ends analysis and learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8,* 463-474.

Sweller, J., Mawer, M., & Howe, W. (1982). Consequences of history-cued and means-end strategies in problem solving. *American Journal of Psychology, 95,* 455-483.

Sweller, J., Mawer, M., & Ward, M. R. (1983). Development of expertise in mathematical problem solving. *Journal of Experimental Psychology: General, 112,* 639-661.

Sweller, J., van Merrienboer, J. G., & Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10,* 251-296.

Tarmizi, R. A., & Sweller, J. (1988). Guidance during mathematical problem solving. *Journal of Educational Psychology, 80,* 424-436.

Tennyson, R. D., & Cocchiarella, M. J. (1986). An empirically based instructional design theory for teaching concepts. *Review of Educational Research, 56,* 40-71.

Tennyson, R. D., Wooley, F. R., & Merrill, M. D. (1972). Exemplar and nonexemplar variables which produce correct concept classification behavior and specified classification errors. *Journal of Educational Psychology, 63,* 144-152.

Trafton, J. G., & Reiser, B. J. (1993). The contributions of studying examples and solving problems to skill acquisition. In M. Polson (Ed.), *Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society* (pp. 1017-1022). Hillsdale, NJ: Erlbaum.

Van Engen, H. V. (1959). Twentieth century mathematics for the elementary school. *The Arithmetic Teacher, 6,* 71-76.

VanLehn, K. (1990). Problem solving and cognitive skill acquisition. In M. I. Posner (Ed.), Foundations of Cognitive Science (pp. 527-579). Cambridge, MA: MIT Press.

VanLehn, K., & Jones, R. M. (1993a). Better learners use analogical problem solving sparingly. In P. E. Utgoff (Ed.), *Machine Learning: Proceedings of the Tenth Annual Conference* (pp. 338-345). San Mateo, CA: Morgan Kaufmann Publishers.

VanLehn, K., & Jones, R. M. (1993b). What mediates the self-explanation effect? Knowledge gaps, schemas or analogies? In M. Polson (Ed.), *Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society* (pp. 1034-1039). Hillsdale, NJ: Erlbaum.

Ward, M., & Sweller, J. (1990). Structuring effective worked examples. *Cognition and Instruction, 7,* 1-39.

Webb, N. M. (1991). Task-related verbal interaction and mathematics learning in small groups. *Journal of Research in Mathematics Education, 22,* 366-389.

Wilkerson, L. & Gijselaers, W. H. (1996). Bringing problem-based learning to higher education: Theory and practice. San Francisco: Jossey Bass.

Williams, S. M. (1992). Putting case-cased instruction into context: Examples from legal and medical education. *The Journal of the Learning Sciences, 2,* 367-427.

Williams, S. M & Hmelo, C. E. (Eds.). (1998). Special Issue: Learning through problem solving. *The Journal of the Learning Sciences, 7.*

Wittgenstein, L. (1953). *Philosophical Investigations.* Translated by G.E.M. Anscombe. Oxford: Blackwell.

Zhu, X., & Simon, H. A. (1987). Leaning mathematics from examples and by doing. *Cognition and Instruction, 4,* 137-166.

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