Chapter 8
What Problem Solvers Know: Cognitive Readiness for Adaptive Problem Solving

Richard E. Mayer

8.1 Introduction

Adaptive problem solving involves the ability to invent solutions to problems that the problem solver has not encountered before. In adaptive problem solving, problem solvers must adapt their existing knowledge to fit the requirements of a novel problem, including a novel problem situation that may change over time. Mayer and Wittrock (2006) refer to this situation as one that requires *problem-solving transfer*.

Consider the problem shown in Fig. 8.1. You are shown a diagram depicting a car's braking system and asked to troubleshoot what could cause it to fail. For people who are not expert car mechanics, answering this question requires adaptive problem solving. For example, some acceptable answers are that there may be a leak in the brake tube or there is too much space between the piston and the cylinder. Even after receiving a multimedia presentation on how a car's braking system works, most novices have difficulty in solving the brake problem (Mayer, 2009).

Next, consider the problem shown in Fig. 8.2. This problem comes in level 10 (i.e., an embedded transfer test) of an educational game intended to teach how electrical circuits work (Johnson & Mayer, 2010; Mayer & Johnson, 2010). Again, for people who are not experts in electronics, this problem requires adaptive problem solving. The correct answer is "same." Even after playing through nine levels of the game intended to teach basic principles of electric flow in circuits, a substantial proportion of players give the wrong answer.

Finally, consider the problem shown in Fig. 8.3. You are shown a diagram depicting part of the process of a solar cell and asked to troubleshoot what could go wrong. If you are not an expert in this field, this is an adaptive problem-solving situation for you. For example, some acceptable answers are that there are no free

R.E. Mayer (✉)
Department of Psychology, University of California, Santa Barbara,
Santa Barbara, CA 93106, USA
e-mail: mayer@psych.ucsb.edu

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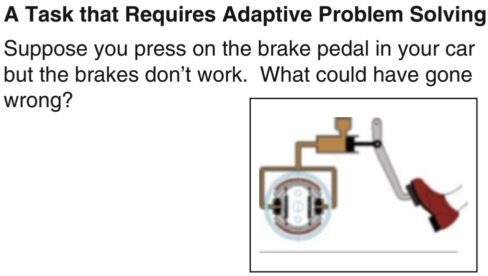

Fig. 8.1 The brake problem

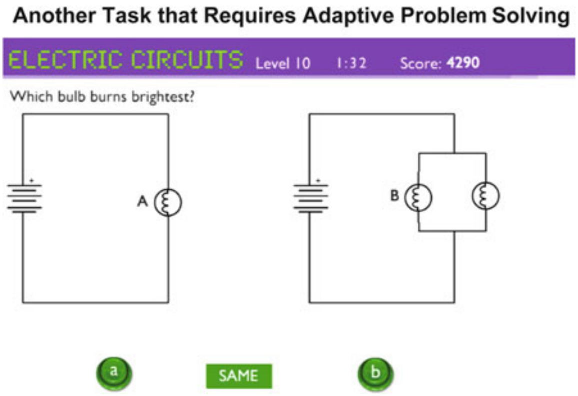

Fig. 8.2 The bulb problem

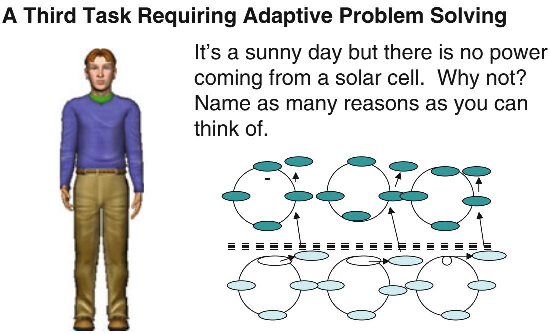

Fig. 8.3 The solar cell problem

electrons on the top layer or no free bonding sites on the bottom layer. After viewing a PowerPoint presentation delivered by an onscreen agent, most learners in our studies still have much difficulty in solving this problem (Mayer & DaPra, 2012).

In short, Figs. 8.1–8.3 represent three examples of adaptive problem solving based on research studies in our lab at the University of California, Santa Barbara. In each example of adaptive problem solving, the problem solver must adapt to a new situation that he or she has not encountered before. Preparing people to be ready to engage in adaptive problem solving constitutes a major challenge for

Table 8.1 Three components in cognitive readiness for adaptive problem solving

Component	Issue
Science of learning	What do you need to know to be ready for adaptive problem solving?
Science of assessment	How can we know what you know?
Science of instruction	How can we help you learn what you need to know to be ready for adaptive problem solving?

trainers and trainees. In short, cognitive readiness for adaptive problem solving refers to being ready to solve novel problems.

In this chapter, I examine three issues concerning cognitive readiness for adaptive problem solving as summarized in Table 8.1. First, based on the science of learning, an important issue concerns specifying what someone needs to know in order to be ready for adaptive problem solving. Second, based on the science of assessment, an important issue concerns how to determine what someone knows. Third, based on the science of instruction, an important issue concerns discovering effective instructional methods that help people learn what they need to know to be ready for adaptive problem solving. As you can see, the thesis of this chapter is that knowledge is at the heart of cognitive readiness—including how to specify the needed knowledge, how to assess whether learners have it, and how to help learners create it. I examine these three issues in the next three sections of the chapter, respectively.

8.2 Science of Learning: What Is Cognitive Readiness for Adaptive Problem Solving?

8.2.1 Role of Knowledge in Adaptive Problem Solving

The science of learning is the scientific study of how people learn. Learning is a change in the learner's knowledge. An important contribution of the science of learning involves techniques for specifying the desired knowledge change—including the knowledge needed to support adaptive problem solving.

Cognitive readiness for adaptive problem solving depends on the learner's knowledge. Table 8.2 lists five kinds of knowledge that support cognitive readiness for adaptive problem solving—facts, concepts, procedures, strategies, and beliefs (Anderson et al., 2001; Mayer, 2008). People may need to integrate all five kinds of knowledge in order to perform well on tasks requiring adaptive problem solving. Strategies include metacognitive strategies for monitoring and controlling one's cognitive processing on a problem-solving task. Beliefs can affect the learner's motivation to initiate and maintain efforts to solve a problem.

As you see, the learner's knowledge plays an essential role in adaptive problem solving. I use knowledge in the broad sense to include all five kinds of knowledge listed in Table 8.2. This analysis is equivalent to the classic distinction among knowledge (which corresponds to facts and concepts), skills (which corresponds to procedures and strategies), and attitudes (which corresponds to beliefs).

Table 8.2 Five kinds of knowledge that support cognitive readiness for adaptive problem solving

Kind	Description	Example
Facts	Factual knowledge about a domain	Brake fluid contains ethylene glycol
Concepts	Categories, schemas, models, principles	A piston in a cylinder is like a syringe
Procedures	Step-by-step processes	Conversion of 1/2 in. to millimeters
Strategies	General methods	Break a problem into parts
Beliefs	Thoughts about one's cognition	"I am good at working with mechanical devices"

8.2.2 A Closer Look at Adaptive Problem Solving

In order to specify the knowledge required for readiness for adaptive problem solving, it is useful to clarify the nature of problems and problem solving.

What is a problem? A problem exists when (a) a situation is a given state, (b) the problem solver's goal is to have the situation in a desired state, and (c) there is no obvious way to move from the given state to the desired state. The Gestalt psychologist Karl Duncker (1945, p. 1) eloquently summarized this classic definition as, "A problem exists when a living creature has a goal but does not know how the goal is to be reached."

It is customary to distinguish between routine and nonroutine problems. With *routine problems*, the problem solver knows a solution method. For example, for most adults, "What is 22 × 155?" is a routine problem because they know the procedure for long multiplication. With *nonroutine problems*, the problem solver does not immediately know a solution method and therefore must invent one. For example, for nonexperts, "How can we make a solar cell more effective?" is a nonroutine problem. As you can see, technically, routine problems do not meet the definition of a problem because "there is an obvious way to move from the given state to the goal state" (or to put it another way, the problem solver "knows how the goal is to be reached"). Thus, adaptive problem solving refers to solving nonroutine problems rather than routine problems.

It is also customary to distinguish between well-defined and ill-defined problems. A *well-defined problem* has a clear statement of the givens, goals, and allowable moves. Examples include solving arithmetic problems or playing a game of chess. An *ill-defined problem* does not have a clear statement of the givens, goals, and/or allowable operators. For example, "Solve the energy crisis" is an ill-defined problem because what you are allowed to do (i.e., the allowable moves) are not clearly specified, nor is the desired goal state. Adaptive problem solving generally refers to solving ill-defined rather than well-defined problems.

What is problem solving? Problem solving is directed cognitive processing. Problem is directed because it seeks to achieve a goal. Problem solving is cognitive because it occurs in the problem solver's mind and must be inferred indirectly through the problem solver's behavior. Problem solving is processing because it involves the mental manipulation of knowledge representations in the problem solver's cognitive system. The Gestalt psychologist Karl Duncker (1945, p. 1) eloquently captured this definition in his classic description, "Whenever one cannot go from the given state to the desired state simply by action, then there is recourse to thinking. Such thinking has the task of devising some action which may mediate between the existing and desired situations." As you can see, figuring out how to accomplish a goal is the essence of problem solving.

How does problem solving work? Problem solving involves two major phases—*problem representation*, in which the problem solver constructs a mental representation of the problem—and *problem solution*, in which the problem solver devises and carries out a solution plan. Although there are several conceptions of how problem solving works (Mayer, 1995), the most prominent explanation is that problem solving occurs when the problem solver reformulates the problem—that is, conceives of the givens or the goal in a new way. The Gestalt psychologist Karl Duncker (1945, p. 1) eloquently summarized this idea as, "What is really done in any solution of problems consists in formulating the problem more productively." Once the problem solver can represent the problem more productively, it is easier to arrive at a solution plan.

What is adaptive problem solving? In light of this analysis, I can expand on the definition of adaptive problem solving. Adaptive problem solving is a form of problem solving that requires a series of problem reformulations or continual reevaluation of problem formulations in light of changing conditions. In short, adaptive problem solving occurs when a problem solver continually revises how he or she represents the problem (and its solution plan) in light of the changes in the problem situation.

8.3 Science of Assessment: How Can We Measure Cognitive Readiness for Adaptive Problem Solving?

The science of assessment is the scientific study of how to determine what people know. For example, Table 8.3 presents example assessment items for each of the five kinds of knowledge required for cognitive readiness—facts, concepts, procedures, strategies, and beliefs.

Although these items may tap individual aspects of the required knowledge, it is also important to assess ways of using this knowledge that go beyond simply remembering. Table 8.4 summarizes six kinds of cognitive processes that may be tapped by assessment items—remember, understand, apply, analyze, evaluate, and

Table 8.3 Example assessment items for five kinds of knowledge required for cognitive readiness

Kind	Example
Facts	In Ohm's law, *R* stands for ___________
Concepts	What would happen to the rate of current if we added another resistor in parallel?
Procedures	If $V=10$ and $R=2$, compute the value of I
Strategies	In a circuit with a current of 5 A, judge which of several different methods accomplishes the goal of doubling the current
Beliefs	Rate from 1 (strongly disagree) to 5 (strongly agree): I like playing the Ohm's Law Game

Table 8.4 Six kinds of cognitive processes in using knowledge

Kind	Description	Example
Remember	Retrieve relevant knowledge from long-term memory	State the formula for Ohm's law
Understand	Construct meaning from instructional messages	Restate Ohm's law in your own words
Apply	Carry out a procedure in a given situation	Compute the value of *I* given *V* and *R*
Analyze	Break materials into parts; determine how parts relate	Distinguish relevant numbers in a word problem
Evaluate	Make judgments based on criteria	Determine the best way to solve a word problem
Create	Put elements together to form a coherent whole	Plan an essay on the history of Ohm's law

Table 8.5 Four types of transfer questions

Type	Example
Troubleshooting	Suppose you pull up and push down on the handle of a bicycle tire pump but no air comes out. What could have gone wrong?
Redesign	How could you make brakes more effective—that is, how could you reduce the distance needed to stop?
Prediction	What would happen if you reversed the positive and negative wires on an electric motor?
Explanation	What does temperature have to do with lightning formation?

create. This taxonomy is based on a revision of the Bloom's taxonomy of educational objectives (Anderson et al., 2001). As you can see, the latter five processes involve using the learned material in new ways rather than simply remembering it—and thus offer possible techniques for assessing cognitive readiness.

Two ways to measure learning outcomes are retention tests and transfer tests. *Retention tests* focus on remembering by asking the learner to recall or recognize the presented material. For example, after reading a lesson on how a car's braking system works, a learner may be asked, "Write down all you can remember about how a car's braking system works as described in the lesson." *Transfer tests* focus on understanding by asking the learner to evaluate or use the material in a new situation. For example, after a lesson on how a car's braking system works, a learner may be asked, "How would you improve the effectiveness of the braking system described in the lesson?"

The pattern of performance on retention and transfer tests indicates three kinds of learning outcomes (Mayer, 2008, 2009). No learning is indicated by poor performance on retention and transfer tests. Rote learning is indicated by good performance on retention and poor performance on transfer. Meaningful learning is indicated by good performance on retention and transfer tests. Thus, cognitive readiness for adaptive problem solving is evidenced by problem-solving transfer in addition to simply focusing on retention.

As you can see, transfer tests are essential in assessment for cognitive readiness for adaptive problem solving. Table 8.5 provides examples of transfer items that require using the information from a lesson in new situations. In particular, the transfer items involve troubleshooting, redesign, prediction, and explanation of a cause-and-effect system (such as how a pump works, how an electric motor works, how an electric circuit works, or how a solar cell works). Transfer items are intended to require adaptive problem solving.

8.4 Science of Instruction: How Can We Teach Cognitive Readiness for Adaptive Problem Solving?

8.4.1 Which Cognitive Processes During Learning Promote Cognitive Readiness?

The science of instruction is the scientific study of how to help people learn. In particular, effective instruction works because it encourages the learner to engage in appropriate cognitive processing during learning. To understand how to accomplish this goal, let's begin with the cognitive model of multimedia learning as presented in Fig. 8.4. This model reflects three principles of how the human cognitive system works based on research in cognitive science:

- *Dual channels principle*—People have separate channels for processing visual/pictorial and auditory/verbal information.
- *Limited capacity principle*—People can engage in only a small amount of cognitive processing in each channel in working memory at any one time.
- *Active processing principle*—Meaningful learning occurs when people engage in appropriate cognitive processing during learning.

The boxes in Fig. 8.4 represent three memory stores:

- *Sensory memory*—which holds visual and auditory images for a brief time (e.g., less than a quarter of a second) with unlimited capacity
- *Working memory*—which can store and manipulate only a few visual items and a few verbal items at any one time (so they are lost within a half minute if they are not processed)
- *Long-term memory*—which permanently holds a storehouse of organized knowledge with unlimited capacity

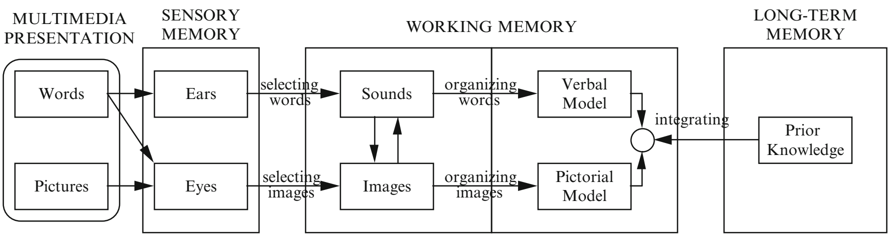

Fig. 8.4 Cognitive theory of multimedia learning

Table 8.6 Three demands on cognitive capacity

Demand	Description	Caused by
Extraneous processing	Cognitive processing that does not support the objective of the lesson	Poor instructional design
Essential processing	Cognitive processing required to mentally represent the presented material	Complexity of the content
Generative processing	Deep cognitive processing aimed at making sense of the presented material	Learner's motivation to exert effort

The arrows in Fig. 8.4 highlight three kinds of cognitive processing during learning:

- *Selecting*—in which the learner attends to relevant aspects of the incoming visual and auditory information (as indicated by the arrows from sensory memory to working memory)
- *Organizing*—in which the learner mentally arranges the pieces of information in working memory into coherent verbal and pictorial representations (as indicated by the arrows within working memory)
- *Integrating*—in which the learner connects the verbal and pictorial representations with each other and with relevant prior knowledge activated from long-term memory (as indicated by the arrow from long-term memory to working memory)

Cognitive readiness for adaptive problem solving is promoted by instructional methods that guide the learner's appropriate cognitive processes during learning—including selecting relevant words and pictures from the presented material, organizing them into coherent verbal and pictorial representations, and integrating the representations with each other and with knowledge activated from long-term memory. An important constraint is that working memory is limited in capacity so only a limited amount of cognitive processing can take place at any one time.

Table 8.6 describes three demands on the learner's cognitive capacity during learning—extraneous processing (which is wasted processing that does not address the instructional objective), essential processing (which consists of selecting and initial organizing), and generative processing (which consists of extensive organizing and integrating). Instruction for cognitive readiness for adaptive problem solving has the challenge of fostering generative processing while at the same time managing essential processing and minimizing extraneous processing.

8.4.2 What Works in Improving Problem-Solving Transfer?

An important accomplishment of the science of instruction for cognitive readiness is a set of evidence-based principles for how to design effective instruction—that is instruction that enables problem-solving transfer. Evidence-based practice refers to the idea that instructional methods should be based on empirical research evidence,

Table 8.7 Five evidence-based principles for reducing extraneous processing

Principle	Description	Example
Coherence [1,2,4]	People learn better when extraneous material is excluded rather than included	Cut out interesting but irrelevant text and graphics
Signaling [1,4]	People learn better when the organization of a lesson is highlighted	Use outlines and section headings for a text lesson
Spatial contiguity [1,2,3,4]	People learn better when corresponding printed words and pictures are near rather than far from each other on the screen or page	Embed relevant words within a graphic rather than as a caption
Temporal contiguity [1,2,4]	People learn better when corresponding spoken words and pictures are presented simultaneously rather than successively	Present narration at the same time as animation rather than before or after
Expectation [2]	People learn better when they are shown the type of test items they will receive following learning	Tell people that after reading this chapter, they will be asked to tell how to define adaptive problem solving

including experiments that compare learning outcomes of students who learn with vs. without a particular instructional feature. Summaries of evidence-based principles include:

1. Mayer's (2005) *Cambridge handbook of multimedia learning*
2. Halpern, Graesser, and Hakel's (2007) *25 learning principles to guide pedagogy and the design of learning environments*
3. Pashler et al.'s (2007) *Organizing instruction and study to improve student learning*
4. O'Neil's (2005) *What works in distance learning: guidelines*

An extraneous overload situation occurs when poor instructional design creates the need for so much extraneous processing that the learner has inadequate remaining cognitive capacity to engage in needed essential and generative processing. Table 8.7 describes five evidence-based principles for reducing extraneous processing—coherence, signaling, spatial contiguity, temporal contiguity, and expectation. The numbers in brackets correspond to the four sources of evidence-based principles listed in the preceding paragraph. As you can see in Table 8.7, learners are less likely to engage in extraneous processing when extraneous words and pictures are eliminated from a lesson (coherence principle), when essential words and pictures are highlighted in a lesson (signaling principle), when corresponding printed words and graphics are near each other on the page or screen (spatial contiguity principle), when corresponding narration and graphics are presented at the same time (temporal contiguity principle), and when learners are told in advance about what to expect for the test (expectation principle).

An essential overload situation occurs when the content of lesson is so complex that the learner lacks enough cognitive capacity to engage in the required essential

Table 8.8 Three evidence-based principles for managing essential processing

Principle	Description	Example
Segmenting [1,2,4]	People learn better when a complex lesson is presented in manageable parts	Break a narrated animation into small segments each with a CONTINUE button
Pre-training [1,4]	People learn better from a complex lesson when they receive pre-training in the names and characteristics of the key concepts	Tell people about the names, locations, and characteristics of the parts before showing them a narrated animation
Modality [1,3,4]	People learn better from a multimedia presentation when words are spoken rather than printed	Accompany an animation with a spoken description rather than onscreen captions

Table 8.9 Four evidence-based principles for fostering generative processing

Principle	Description	Example
Multimedia [1,2,4]	People learn better from words and pictures rather than from words alone	Add relevant graphics to text
Personalization [1,4]	People learn better when words are in conversational style rather than formal style	Use "I" and "you"
Concretizing [2,3]	People learn better when unfamiliar material is related to familiar knowledge	Provide concrete examples or analogies
Anchoring [2,3]	People learn better when material is presented within the context of a familiar situation	Learn about functions within the context of a business financial plan

processing. Table 8.8 describes three evidence-based principles for managing essential processing, thereby freeing capacity for needed essential and generative processing—segmenting, pre-training, and modality. As you can see in Table 8.8, learners are better able to manage essential processing when complex material is broken into bite-sized segments and presented with a continue button (segmenting principle), when learners receive pre-training in the names, locations, and characteristics of key elements (pre-training principle), and when words in a multimedia presentation are presented in spoken form thereby offloading some processing from the visual channel to the verbal channel (modality principle).

An underutilization situation occurs when a learner has the cognitive capacity available for the required essential and generative processing, but the learner is not motivated to exert the effort to engage in this processing. Table 8.9 describes four evidence-based principles for fostering generative processing—multimedia, personalization, concretizing, and anchoring (Mayer, 2009, 2011). As you can see, learners work harder to make sense of the presented material when the lesson contains words and pictures rather than words alone (multimedia principle), when words are presented in conversation style such as using first and second person constructions (personalization principle), when abstract material is explicitly linked to concrete examples or analogies (concretizing principle), and when unfamiliar material is presented within a familiar context or scenario (anchoring principle).

Other evidence-based techniques that encourage generative processing include the testing principle (e.g., having the learner answer practice test items after studying a lesson), the self-explanation principle (e.g., asking the learner to point out anything that does not make sense while reading a lesson), the questioning principle (e.g., asking the learner to produce possible test questions after viewing a presentation), and the elaboration principle (e.g., asking the learner to take notes while listening to a lecture) (Halpern et al., 2007; Mayer, 2011; Pashler et al., 2007). Evidence-based techniques geared for practicing include the feedback principle (e.g., providing a step-by-step explanation for the correct answer after someone attempts to solve a problem), the worked examples principle (e.g., providing a step-by-step explanation of how to solve a problem before asking someone to solve a similar problem), and the guided discovery principle (e.g., asking someone to solve a problem while the instructor provides hints, models how to solve parts of the problem, and offers explanative feedback) (Halpern et al., 2007; Mayer, 2005, 2011; O'Neil, 2005; Pashler et al., 2007). As you can see, the science of instruction is enjoying some success in deriving principles for how to help people learn in ways that prepare them for adaptive problem solving as can be found in Clark and Mayer (2011).

8.5 Conclusion

In conclusion, based on the science of learning, we began with the idea that cognitive readiness for adaptive problem solving depends on the learner's knowledge (i.e., facts, concepts, procedures, strategies, and beliefs). Based on the science of assessment, we seek to assess adaptive problem solving by examining problem-solving transfer tests. Based on the science of instruction, we consider instructional methods that promote cognitive readiness for adaptive problem solving through priming appropriate cognitive processing during learning (e.g., multimedia, personalization, generating, anchoring, testing, self-explanation, and elaboration). In short, understanding cognitive readiness for adaptive problem solving involves specifying the knowledge that enables adaptive problem solving, determining how to assess whether a learner possesses that knowledge, and discovering how to help people acquire it. This line of research is an example of what it means to apply the science of learning to education (Mayer, 2011).

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