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Learners as Information Processors: Legacies and Limitations of Educational Psychology's Second Metaphor

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This essay examines the role of information-processing theories in the historical search for a guiding metaphor of educational psychology. First, I show how information processing can be viewed as the second in a series of three metaphors that developed during this century and, more specifically, as a bridge from associationist to constructivist visions of learning. Second, I provide a definition of information processing based on the premise that humans are processors of information. Third, I distinguish between literal and constructivist interpretations of two key elements in information-processing theory, namely, the nature of information and the nature of processing. Then, I summarize the contributions and limitations of the information-processing approach. Finally, I examine possible future directions for the search for educational psychology's guiding metaphor.

The goal of this essay is to examine the historic role of the information-processing approach to educational psychology, that is, the view of learners as processors of information. In a recent review, I (Mayer, 1992) showed how a progression of three metaphors of learning evolved during the 20th century, with the information-processing metaphor serving as a historic bridge from the associationist metaphor that dominated educational psychology throughout the first half of this century to the constructivist metaphor that has come to dominate the field today. This review is motivated by the premise that a historical review of educational psychology's second metaphor—information processing—can provide insight into the continuing search for a useful metaphor of learning.

Ultimately, this essay concerns the search for a guiding metaphor in educational psychology. Philosophers of science showed how scholarly disciplines are guided by the metaphors held by their constituents (Gentner & Jeziorski, 1993; Kuhn, 1970, 1993; Leary, 1990; Ortony, 1993; Sternberg, 1990). Within the field of psychology, Leary provided a history of how "metaphorical thinking ... has helped to constitute, not merely reflect, scientific theory and practice" and showed how "metaphors ... have guided—and sometimes preempted—investigation in selected areas of psychology" (p. 1). Choosing a guiding metaphor in educational psychology is an important task because "the future of the discipline itself will be affected by the choices of metaphor that psychologists make" (Leary, p. 23).

Because of its link to real-world contexts of learning and development, educational psychology has often been at the forefront of providing psychology with its conceptual underpinnings—that is, with its metaphors. Instead of solely being a field in which concepts developed by basic researchers are applied to educational practice, educational psychology is also a field in which the demands of educational practice shape the development of new metaphors used to guide basic research. For example, the constructivist revolution that challenged information processing was not developed solely in psychological laboratories and passed on to educators but rather was the result of the need to explain what happens in real educational settings. Thus, educational psychology sits at the intellectual crossroads of educational practice and scientific research and is poised to contribute significantly to the search for productive metaphors.

Constructivism is a hot topic in educational psychology, but discussions about constructivism are essentially discussions about the metaphor that should be used to guide the discipline (Bereiter, 1994; Cobb, 1994; Davis, Maher, & Noddings, 1990; Driver, Asoko, Leach, Mortimer, & Scott, 1994; Phillips, 1994, 1995; Steffe & Gale, 1995). Currently, the central tenet of the constructivist metaphor is that humans are knowledge constructors. In order to understand the origins, usefulness, and future of today's dominant metaphor, it is useful to consider its intellectual predecessor.

When cognitive psychology was reborn in the late 1950s, it began with an information-processing approach to human

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cognition. By the 1960s and 1970s, information processing had replaced behaviorism as the dominant approach to psychology. Since that time, cognitive psychology has experienced a constructivist revolution and has continued to mature into a science that is increasingly relevant to education. In this sense, both information processing and constructivism may be viewed as approaches to cognitive psychology. This article examines the information-processing approach by providing a brief historical overview, constructing definitions of information processing, assessing the contributions of information processing, assessing the limitations of information processing, and speculating on future directions.

HISTORICAL OVERVIEW: WHERE DOES INFORMATION PROCESSING FIT?

During the past 100 years, theories of learning and instruction have been based on three metaphors: learning as response strengthening, learning as information processing, learning as knowledge constructing (Mayer, 1992). Table 1 summarizes the characteristics of each metaphor.

Learning as Response Strengthening

The first metaphor views learning as response strengthening, or more appropriately, learning as changing the strength of stimulus–response (S–R) associations. Based predominantly on research on learning in laboratory animals, the response-strengthening view came to dominate psychology during the first half of this century. For example, in his classic monograph, *Animal Intelligence,* Thorndike (1911/1965) summarized how hungry cats placed in a box learned to open a door leading to food by pulling on a loop of string. By observing the cat's behavior across each time it was put in the box, Thorndike noticed changes in the cat's actions. After many sessions, the cat, when put in the box, produced fewer extraneous responses, such as trying to squeeze through any opening, and more quickly pulled the string to open the door.

Thorndike's work was based on the idea that learning involves the strengthening or weakening of associations between a given stimulus situation (such as being put in box) and a given response (such as pulling a loop of string). The major conceptual accomplishment of Thorndike's work was the creation of the two highly influential laws of learning: the law of effect and the law of exercise. The law of effect states,

> Of several responses made to the same situation, those which are accompanied or closely followed by satisfaction to the animal will, other things being equal, be more firmly connected with the situation, so that, when it recurs, they will be more likely to recur; those which are accompanied or closely followed by discomfort to the animal will, other things being equal, have their connections with that situation weakened, so that, when it recurs, they will be less likely to occur. (Thorndike, 1911/1965, p. 244)

The law of exercise states, "Any response to a situation will, other things being equal, be more strongly connected with the situation in proportion to the number of times it has been connected with that situation" (Thorndike, 1911/1965, p. 244). Since Thorndike's pioneering experiments, others, such as Skinner and Hull, improved on Thorndike's research methods and refined the theory. The view of learning as strengthening and weakening of S–R connections dominated American psychology through the 1950s and still is in psychology's arsenal of theories today.

Applying this view to the classroom, it follows that teachers are dispensers of rewards and punishments, and learners are recipients of rewards and punishments. The instructional method suggested by this metaphor is drill and practice. For example, in an early version of drill and practice called *recitation,* the teacher asks a question that has a simple (usually one word) answer, calls on a student to give the answer, punishes the student if the answer is wrong, and praises the student if the answer is correct. Cuban's (1984) *How Teachers Taught* contains descriptions of an early 1900s high school classroom in which "the teacher … had acquired the habit of conducting recitations at the rate of from 100 to 200 questions and answers per classroom period of 45 minutes" (p. 28). Teachers who so vigorously applied the re-

TABLE 1
Three Metaphors of Learning

Learning	*Major Era*	*Research Base*	*Teacher's Role*	*Student's Role*	*Typical Instructional Method*
Response strengthening	1900s–1950s	Lab animals on artificial tasks	Dispenser of rewards and punishments	Recipient of rewards and punishments	Drill and practice on basic skills
Information processing	1960s–1970s	Humans on artificial tasks	Dispenser of information	Recipient of information	Textbooks and lecturing
Knowledge constructing	1980s–1990s	Humans on realistic tasks	Guide for exploring academic tasks	Sense maker	Discussion, guided discovery, supervised participation in academic tasks

sponse-strengthening metaphor in their classrooms had become "drillmasters instead of educators" (p. 29).

Learning as Information Processing

The second metaphor views learning as information processing. This view developed, in part, as a reaction against the response-strengthening metaphor:

> The main objection to the prevailing theory, which makes one kind of connection the basis of all learning, is not that it may be incorrect, but that in the course of psychological research it has prevented an unbiased study of other possible kinds of learning. (Katona, 1940, pp. 4–5)

Katona argued that there are two kinds of learning: rote learning in which "connections [are] established by the conditioned-reflex technique or by repeating the same ... responses ... as in all forms of drill" and meaningful learning in which learners achieve "insight into a situation" or "understanding of a procedure" (p. 5).

For example, Wertheimer (1959) provided a classic example of the distinction between learning by rote and learning by understanding. In the first case, students learned to compute the area of a parallelogram by memorizing the procedure of measuring the base, measuring the length of the perpendicular, and multiplying them together. This kind of learning, which Wertheimer called *reproductive thinking,* allows students to solve problems but does not promote transfer to novel problems. In the second case, students learned that they could cut a triangle from one of the parallelograms and place it on the other end, forming a rectangle, whose area they already knew how to compute. Wertheimer referred to this kind of learning as *productive thinking* because students performed well both on retention and transfer problems. In short, Katona (1940) claimed, "If the two kinds of learning differ from each other they must yield different results" (p. 5). The major payoff for learning by understanding lies not in retention but rather in transfer.

By the late 1950s and the 1960s, the strangle hold of the response-strengthening metaphor on American psychology had been successfully challenged. Although Gestalt psychologists such as Katona and Wertheimer were among the first to offer alternatives to the response-strengthening view, their vision of learning by constructive understanding was not the next metaphor to gain acceptance in the psychology of learning (Mayer, 1995). The consensus among modern cognitive psychologists about the Gestalt view of cognition is that "they were right, but they lacked a language in which to make their ideas clear" (Johnson-Laird, 1988, p. 19). Thus, the cognitive revolution ripened in the 1960s and 1970s and overthrew S–R associationism as the sole basis for learning theory. However, rather than building on vague Gestalt conceptions of insight, the emerging cognitive psychology replaced the response-strengthening metaphor with a metaphor based on an exciting new technological creation—the electronic digital computer.

Invented in the late 1940s and mass produced in the 1950s, electronic computers served both as a metaphor of human learning and as a psychological research tool. The human–computer analogy is based on the observation that both computers and humans engage in cognitive processes such as learning (or acquiring knowledge), remembering (or retrieving knowledge), making decisions, answering questions, and so on. Computers perform cognitive tasks by processing information—taking symbols as input, applying operators to the input, and producing output—so it follows that perhaps humans are also information processors. For example, Lachman, Lachman, and Butterfield (1979) described the human–computer analogy as follows:

> Computers take symbolic input, recode it, make decisions about it, and give back symbolic output. By analogy, that is most of what cognitive psychology is about. It is about how people take in information, how they recode and remember it, how they make decisions, how they transform their internal knowledge states, and how they translate these states into behavioral output. (p. 99)

Lachman, Lachman, and Butterfield (1979) pointed out that input is different from a stimulus, output is different from a response, and applying a mental operation is different from strengthening or weakening an S–R association.

According to the information-processing metaphor, learning is a process of knowledge acquisition in which information is transmitted from the teacher to the learner. It follows that teachers are dispensers of information, and learners are information processors. The most typical instructional methods suggested by the information-processing metaphor are lecturing and presenting textbooks.

Learning as Knowledge Constructing

The third metaphor views learning as knowledge constructing. As researchers expanded the scope of their research beyond contrived laboratory tasks, the constructive nature of learning became more apparent. By the late 1970s, it became clear that the "development of cognitive psychology in the last few years has been disappointingly narrow, focusing inward on the analysis of specific experimental situations rather than outward toward the world beyond the laboratory" (Neisser, 1976, p. xi). In his classic book, *Cognition and Reality,* Neisser challenged cognitive psychologists to examine cognition in the real world:

> The study of information processing has momentum and prestige, but it has not yet committed itself to any conception of human nature that could apply beyond the confines of the

> laboratory. ... There is still no account of how people act or interact with the ordinary world. ... If cognitive psychology commits itself too thoroughly to this model, there may be trouble ahead. Lacking in ecological validity, indifferent to culture, even missing some of the main features of perception and memory as they occur in ordinary life, such a psychology could become a narrow and uninteresting specialized field. (pp. 6–7)

The call for more ecologically valid research served to bring on the widespread acceptance of psychology's third metaphor—learning as knowledge constructing—in the 1980s and 1990s. It is important to note that the call for ecological validity can be traced to the demands of educators and educational psychologists who argued for studying individual learners on academically valid tasks. For example, in the early 1900s Binet attacked "sterile experimental conditions" (Wolf, 1973, p. 91) created by researchers who "seem never to have put their noses to the window of their laboratories" (p. 315). Like the critics of classic cognitive psychology, Binet questioned the value of artificial laboratory research on decontextualized tasks:

> Subjects go into a little room, respond by electrical signals, and leave without so much as a word to the experimenter. ... The latter want simple and precise results, even to carrying them to three decimal places and measuring them to 1/1000ths seconds. Their aim is simplicity, but it is only a factitious one, artificial, produced by the suppression of all troublesome complications. This simplicity comes about only when we efface all individual differences, thus coming to conclusions that are not true. (cited in Wolf, 1973, p. 91)

If cognitive psychology was to move beyond contrived laboratory tasks, where would the new ecologically valid tasks come from? An important venue for psychology's research agenda of the 1980s and 1990s has been academic tasks. Psychologies of subject matter have flourished, including advancements in the psychologies of reading, writing, mathematics, and science learning. Instead of asking how people learn in general, psychologists of subject matter ask how people learn to read, to write, to think mathematically, or to think scientifically (Resnick & Ford, 1981). In short, a focus on academic tasks helped to revitalize cognitive psychology. The transition from information processing to cognitive constructivism can be traced to the shift from research on artificial laboratory tasks to real academic tasks.

According to the constructivist metaphor, learning is a process of knowledge construction. Teachers are cognitive guides for academic tasks, and learners are sense makers. This view recently acquired a dominant status under the banner of cognitive constructivism and suggests instructional reforms such as discussion methods, guided discovery methods, and supervised participation in meaningful academic tasks.

A potential fourth metaphor that is still emerging under the banner of social constructivism views learning as social negotiation and learners as social negotiators. Overall, Steffe and Gale (1995) identified six versions of constructivism: "social constructivism, radical constructivism, social constructionism, information-processing constructivism, cybernetic systems, and sociocultural approaches" (p. xiii). However, the definitional and research bases for some of the versions are not yet fully developed.

The remainder of this article focuses on the role of educational psychology's second metaphor—learners are information processors—in the evolution of constructivist views of learning and instruction.

WHAT IS INFORMATION PROCESSING?

Humans are processors of information. The mind is an information-processing system. Cognition is a series of mental processes. Learning is the acquisition of mental representations. These statements represent the major tenets of the information-processing conception of human cognition. During the 1950s, 1960s, and 1970s, exciting new answers emerged to questions concerning the nature of the human mind and its operation—answers that eventually coalesced into what has been called information-processing psychology. The answers borrowed heavily from advances in computer technology and computer programming and were based on a computer analogy.

Humans as Information Processors

The overarching premise of information-processing psychology is that humans are processors of information. For example, in their classic of cognitive psychology, *Human Problem Solving,* Newell and Simon (1972) proclaimed, "The present theory views humans as processors of information" (p. 5). According to this view, humans take information as input, apply one or more mental operators to that information, and produce information as output.

The view of humans as information processors is a modern instantiation of a 250-year-old philosophical tradition that holds that "man is a machine" (de la Mettrie, 1748/1912, p. 148). What was new about the information-processing metaphor was not the view of humans as machines but rather the determination of what kind of machine best epitomized humans. Neisser (1976) noted that "the coming of the computer provided a much needed reassurance that cognitive processes were real" (p. 6). Similarly, Johnson-Laird (1988) made the case for the computer analogy:

> The invention of the programmable digital computer, and more importantly its precursor, the mathematical theory of computability, have forced people to think in a new way about the mind. ... All the computer ever does is to manipulate binary numerals, but fifty years of research has failed to

find a process that cannot be modeled by these manipulations. (pp. 34–35)

The computer analogy can be analyzed into three components that form the basis for three themes of information-processing psychology: hardware, such as viewing the mind as an information-processing system; software, such as viewing cognition as applying cognitive processes; and data, such as viewing learning as knowledge acquisition. These themes are summarized in Table 2.

Mind as an Information-Processing System

First, if humans are information processors, the human mind can be conceived as an information-processing system. Based on a computer analogy, the human mind is like a computer. It can be described in the same way that computer hardware is described—in terms of memory stores and control processes. It follows that a central goal of information-processing psychology is to describe the architecture of the human information-processing system—a feat that was bravely attempted by Atkinson and Shiffrin in 1968. Although the model has been amended, modified, and effectively challenged, the description of the architecture of the mind remains as a central tenet of information-processing psychology.

According to this view, mental life can be analyzed into mental processes and mental representations; when a mental process is applied to a mental representation, the output is a new mental representation. The distinction between processes and data structures is fundamental to theories of computer programming and forms the basis for the final two tenets of information-processing psychology.

Cognition as Applying Cognitive Processes

The second theme is that any cognitive task can be analyzed into a series of information-processing stages. In each stage, a cognitive process is applied. If the mind is like a computer, a series of cognitive processes is like a computer program. Although this view of cognition dates back to the work of Donders in the 1800s, the cognitive analysis of intellectual tasks reemerged in the 1960s and 1970s (Posner, 1978). It follows that a major goal of cognitive psychology is to identify the software that is available for human information processing. For example, Posner noted that cognitive psychology "seeks to isolate elementary mental operations" (p. 6). Newell and Simon (1972) expressed this idea by proposing that humans possess "a number of elementary information processes that operate upon symbol structures" (p. 29) and human cognition "consists in executing sequences of elementary information processes" (p. 30).

Learning as Knowledge Acquisition

The third theme is that learning involves the acquisition of knowledge. Mental representations of knowledge are at the heart of the information-processing approach. In his classic, *Cognitive Psychology,* Neisser (1967) proclaimed, "Information is what is transformed, and the structured pattern of its transformations is what we want to understand" (p. 8). If knowledge is a series of symbols, then learning becomes the transmission of symbols—often in verbal form—from a teacher to a learner.

TWO VIEWS OF INFORMATION PROCESSING

If humans are processors of information, the nature of information and processing become the central issues of cognitive psychology. For example, in *The Promise of Cognitive Psychology* (Mayer, 1981), I defined cognitive psychology as "the scientific analysis of human mental processes and memory structures" (p. 1). From the very start, the information-processing approach contained conflicting conceptions of human cognition—conflicts concerning the nature of information and processing. Early work in information processing defined mental representations as symbols (Newell & Simon, 1972) and mental processing as computation (Johnson-Laird, 1988), but alternative conceptions of the nature of information and processing soon emerged.

The information-processing model is subject to many interpretations, including two broad classes that I call the *literal* view and the *constructivist* view. The two views differ primarily in their conceptions of the nature of mental representations and mental processes, as summarized in Table 3.

TABLE 2
Three Themes of the Information Processing Metaphor

Theme	*Example*
Mind as an information-processing system	Like computer hardware, the mind consists of memory stores and control processes for the flow of information.
Cognition as applying cognitive processes	Like computer programs, cognitive processing consists of applying a series of cognitive processes in which the output of one process becomes the input for the next cognitive process.
Learning as the acquisition of mental representations	Like computer data structures, mental representations consist of discrete pieces of information and are the input and output of cognitive processing.

TABLE 3
Two Views of the Information-Processing Metaphor

View	*Content*	*Activity*	*Learner*
Literal	Information	Processing	Performs a series of discrete mental operations on input information and stores the output
Constructivist	Knowledge	Constructing	Actively selects, organizes, and integrates incoming experience with existing knowledge

Literal Interpretation of Information Processing

According to a literal interpretation of the information-processing model, mental representations are simply pieces of information. Information is represented by symbols and can be mathematically evaluated. Information is an objective entity that exists independent of where it is being stored. For example, Shannon and Weaver (1949) provided a mathematical theory of information in which the smallest unit of information is the bit—a piece of information that allows a binary choice between. In its purest form, any piece of information can be digitized as a string of 0s and 1s. If mental representations are pieces of information (represented as strings of symbols), the goal of learning and instruction becomes to take information from outside the learner's head and place it inside the learner's head.

According to a literal interpretation of the information-processing model, a cognitive process is a discrete procedure in which information is input, operators are applied to the input information resulting in the creation of new information, and the new information is output. Thus, a cognitive process can be conceived of as a box in a flow chart with an arrow leading into the box and an arrow leading out of the box. The incoming arrow corresponds to a set of symbols that is input, the box corresponds to manipulations that are performed on the symbols, and the arrow leading out of the box corresponds to a set of symbols that is output. In short, a cognitive process is simply a symbol manipulation algorithm, that is, a mental computation.

Constructivist Interpretation of Information Processing

In contrast, the constructivist interpretation of the information-processing model views memory representations as knowledge rather than as information. Knowledge can be schematic, whereas information is atomistic; knowledge can be general, whereas information is concrete; knowledge is mediated, whereas information is objective; knowledge is coherent, whereas information is arbitrary. For example, one kind of knowledge is a mental model—a mental representation of how some system works.

According to the constructivist interpretation of the information-processing model, mental processing involves an active search for understanding in which incoming experience is reorganized and integrated with existing knowledge. Three basic processes in active learning are selecting relevant incoming experiences, organizing them into a coherent representation, and integrating them with existing knowledge. In this view, processing is not a series of discrete algorithms executed in order, but rather a coordinated collection of processes aimed at making sense out of incoming experiences.

In summary, the literal view of information processing is the classic, or nonconstructivist, view because it is tightly tied to the computer metaphor. It involves a direct application of the computer metaphor to human cognition. In comparison, the constructivist view of information processing is the transitional, or liberal, view because it involves adjusting the computer metaphor to be more consistent with existing research on human cognition. The emergence of the constructivist interpretation of information processing fosters the next logical step in a movement toward the widespread acceptance of psychology's third metaphor—humans as knowledge constructors.

The multiplicity of interpretations of the information-processing metaphor—reflected in the distinction between constructivist and literal interpretations—makes it difficult to assess the contributions and limitations of information processing. On the one hand, criticisms of information processing are sometimes directed at a literal version (Derry, 1992), whereas commendations are based on a constructivist version (Mayer, 1992). In reviewing the legacies and limitations of information-processing psychology, I find that many of the lasting contributions can be attributed to the view of mental representations as knowledge and of cognitive processing as constructing, whereas many of the limitations apply mainly to the view of mental representations as bits of information and of cognitive processing as computing.

LEGACIES OF INFORMATION PROCESSING

The continuing evolution of cognitive theories of learning and instruction is based on important legacies from information-processing theory. The positive contributions of the constructivist version of information processing involve techniques for describing what learners know—that is, the nature of mental representations constructed during learning—and how learners learn—that is, the nature of cognitive processing produced during learning. Emerging constructivist theories incorporate these useful aspects of information-processing theory but reject the nonuseful ones.

Some of the lasting legacies are summarized in the left side of Table 4 and include the following:

TABLE 4
Some Legacies and Limitations of the Information-Processing Metaphor

Legacies	*Limitations*
Enabled the rebirth of cognitive psychology by providing an alternative to the behaviorist view of learning	Initially ignored the role of affect, interest, and motivation in learning; initially ignored the role of social, cultural, and epistomological aspects of learning; initially ignored the role of biological, physiological, and evolutionary aspects of learning
Created a unified framework that stimulated research and theory, including emphasis on capacity limitations in information processing	Initially proposed a rigid architecture of the mind
Highlighted the role of mental representation in learning, including the structure of knowledge	Initially viewed the content of learning as information rather than knowledge
Highlighted the role of mental processing in learning, including individual differences in cognitive processing, domain specificity of cognitive processes, and the role of learning strategies	Initially viewed mental activity as automatic processing rather than effortful constructing
Encouraged a transition from research on animal learning to research on human learning, which eventually led to a vision of learning as an active process	Initially focused on contrived laboratory tasks rather than realistic academic tasks

1. The information-processing metaphor allowed psychology to move away from behaviorist conceptions of learning and offered cognitive psychology a powerful new conception. In particular, the information-processing metaphor was the instrument that enabled psychology's paradigm shift from S–R behaviorism to cognitive psychology. Perhaps information processing's most important legacy is that it provided a much needed alternative to the S–R association as the only unit of learning. It set into motion a cognitive revolution that has come to dominate psychology and continues to develop.

2. The information-processing metaphor provided a unified framework for describing the human information-processing system. The proposed models of the human information-processing system stimulated useful research and eventual changes in our conceptions of human information processing. Although many of the initial assumptions have been modified or even rejected, continuing work is theoretically useful and educationally relevant—such as research on the limited capacity of working memory (Baddeley, 1986; Gathercole & Baddeley, 1993) and on the distinction between visual and verbal information-processing systems (Paivio, 1986). In a thoughtful review of the criticisms and contributions of the information-processing model, Gardner (1985) concluded, "My own feeling is that it is premature to call off efforts to locate and describe a general cognitive system" (p. 132).

3. The information-processing metaphor focused attention away from behavior and toward mental representations. As such, the information-processing metaphor led to the development of modern theories of knowledge—including the study of schemas, mental models, and conceptual change.

4. The information-processing metaphor focused attention away from the strengthening and weakening of S–R associations and toward the analysis of learning and cognition into component processes and metaprocesses. The focus on precisely described information processes stimulated advancements in the study of learning and thinking strategies, the teaching of cognitive strategies, the remediation of specific information-processing deficits in special education, and the assessment of cognitive strategies in the context of performance on academic tasks.

5. The information-processing metaphor encouraged a transition from research on animal learning to human learning. By focusing on human information processing, the new metaphor helped create an environment in which theories of learning were based on humans rather than on lab animals.

Cognitive process instruction represents an excellent example of the successful application of the information-processing metaphor to instruction (Pressley, 1990; Weinstein & Mayer, 1985). During the 1980s, an increasing number of researchers showed how direct instruction in learning strategies and thinking strategies could improve student performance in a variety of subject matter areas (Mayer, 1987). For example, in the subject domain of mathematics learning, Lewis (1989) showed how mathematical problem solving improved when students learned strategies for how to translate word problems into diagrams. In the subject domain of science learning, Cook and Mayer (1988) showed how students' comprehension of their science textbooks improved when they learned strategies for how to take structured notes. In the domain of writing, Fitzgerald and Teasley (1986) taught students to use cognitive processes for writing organized narratives. In line with successful programs such as these, Weinstein and Mayer (1985) argued that cognitive process instruction should be recognized as an important part of school curricula.

The continuing transition in research topics eventually encouraged the transition to new conceptions of learning as an active rather than a passive process, as a domain-specific rather than a domain-general process, and as a individually based rather than a monolithic process. The information-processing metaphor of the 1960s and 1970s touched off a paradigm shift in psychology that enabled the transition to the constructivist metaphor in the 1980s and 1990s. When psychologists and educators started viewing learners as information processors rather than as response strengtheners, a chain of events was set into motion that continues to drive the field today. When psychologists and educators started asking questions about the nature of mental representations and the nature of mental processing, they were compelled to study cognition in educational settings. The challenge of understanding how people learn in educational settings has prompted the emergence of constructivist views of learning, again reflecting educational psychology's role as a source for psychology's metaphors.

Finally, the information-processing metaphor, like the response-strengthening metaphor before it, demonstrated how the study of human learning and instruction could be a scientific study. Using rigorous methods, precise theories were constructed and tested based on empirical data. In contrast to largely philosophical approaches, the history of the information-processing metaphor demonstrated how the scientific method can be applied to the study of human learning and instruction. Instead of serving as a doctrine to which all else must conform, the information-processing metaphor served to generate scientifically testable theories that eventually led to its own revision. Thus, an often overlooked legacy of the information-processing metaphor is the value placed on settling arguments by using methodologically sound research studies rather than by relying on the popular opinion of experts.

LIMITATIONS OF INFORMATION PROCESSING

The evolution of cognitive theories of learning and instruction involved overcoming serious limitations of information-processing theory concerning the nature of information and processing. The limitations of some versions of information-processing theory rest in the atomistic view of information as a commodity that could be taken from the outside and placed directly within a learner's memory and the mechanistic view of processing as applying a symbol-manipulation algorithm to information in the learner's memory. The major shortcoming of information-processing psychology, perhaps, was the failure to acknowledge that humans process information for a purpose. The search for what is missing from this view has helped to enrich the field.

Among some of the more notable limitations of information-processing psychology are the following:

1. The information-processing metaphor was an incomplete transition away from S–R behaviorism. For example, in their landmark treatise, *Plans and the Structure of Behavior,* Miller, Galanter, and Pribrim (1960) showed how a feedback loop called a *plan* could replace the S–R association as the unit of analysis for cognition. However, when they looked closely at the idea that cognition can be described as a series of algorithms, they were forced to confess "It suddenly occurred to us that we were subjective behaviorists" (p. 211). In spite of the implication that learning is an active and constructive process, a literal version of the information-processing metaphor is most consistent with the view of learning as a passive, atomistic, and mechanical process.

In short, interpreted in its most literal sense, the human–computer analogy is incomplete. Its rigid view of cognition ignores important aspects of the psychological research base—including the findings showing that learning is an active, schematic, and effortful process. It also ignores emotional, affective, and motivational aspects; social, cultural, and epistemological aspects; and biological, physiological, and evolutionary aspects.

2. The classic information-processing model was an incomplete framework for describing the architecture of the human mind. The lines dividing sensory memory, short-term memory, and long-term memory are not as firm today as they were 25 years ago, and many of the basic tenets of the early models have been seriously challenged by empirical research. In a retrospective review of the information-processing approach, Neisser (1976) proclaimed, "the villains of this piece are the mechanistic information-processing models, which treat the mind as a fixed-capacity device for converting discrete and meaningless inputs into conscious percepts" (p. 10). The box models tended to downplay the role of executive control of cognitive processing.

3. The classic information-processing conception of mental representation was incomplete. The view of information as a commodity—as a set of symbols—led to view of learning as process of information transmission from teacher to student. The view of learning as the acquisition of new S–R associations changed to learning as the acquisition of symbols. In both the behaviorist and literal cognitive views, learning was a passive process in which something is added to the learner's repertoire. Although this view seemed to account for rote learning of word lists, it was unable to account for meaningful learning in more complex situations. When researchers examined more complex learning situations, they found the need to describe learning as a process of assimilation to schemas, of building a succession of mental models, and of an active search for structural coherence.

4. The classic information-processing conception of cognitive processing was incomplete. An early goal of information-processing psychology was the identification of all of the basic cognitive processes used by humans for cognitive tasks. In a retrospective review, Glass, Holyoak, and Santa (1979) summarized the limitations of this search:

> A short time ago ... hopes were high that the analysis of information processing into a series of discrete stages would offer profound insights into human cognition. But in only a few short years the vigor of this approach was spent. It was only natural that hopes that had been so high should sink low. (p. ix)

One of major limitations of the search for basic cognitive processes was the assumption that processes, like subroutines in a computer program, were discrete atoms that were applied in serial order. Although this view might correspond to what happens for very simple, well-learned tasks, a mounting research base challenged the separability and seriality of cognitive processes for complex, creative tasks (Posner, 1978). In short, a literal version of information-processing psychology ignored the fact that cognitive processing does not occur in a vacuum but rather is performed in the context of larger tasks. When more complex tasks were studied it became clearer that learners need to be able to determine which processes are appropriate for a given task, to orchestrate the processes, and to monitor the processes—that is, learners need to use metacognitive processes.

5. The classic information-processing conception was based largely on research on human learning conducted in artificial laboratory environments. Although the research methodology was rigorous and the theories were precise, sometimes the studied tasks seemed artificial, contrived, and trivial. In a historical analysis, Gardner (1985) noted,

> Even when results held up reasonably well, there was increasing skepticism about their actual value. ... Information-processing psychologists in the Donders–Sternberg–Sperling tradition developed increasingly elegant models about effects which did not prove robust when they were changed in various ways; nor did these models clearly add up to a larger, more comprehensive picture of how information is processed under real-life situations. Eventually many of these researchers themselves abandoned this tradition and went on to other lines of study. (p. 124)

What was needed was a shift to the study of human cognition in more realistic contexts. In a sense, by holding too tightly to a literal view of the human–computer analogy, information-processing psychology took the field on a 20-year detour around a central challenge in cognitive science—the explanation of human cognition in realistic settings.

Overall, the information-processing metaphor, like the response-strengthening metaphor it replaced, can be criticized not so much for being incorrect as for being incomplete. By focusing solely on the rational side of human cognition, it ignored the affective, social, and biological aspects of cognition. By focusing too rigidly on the study of simple tasks in artificial context, it ignored the metacognitive aspects of cognition. By limiting its perspective to the literal interpretation of cognition as performing computations on symbols, it ignored situations in which learners actively construct new knowledge. However, in spite of its limitations, cognitive psychology demonstrated an exhilarating tendency for self-correction and progress.

To a large extent, the limitations and eventual revision of information processing came about because of the shift in research focus from human learning on simple, artificial tasks to human learning on real-world tasks. The amazing survival of cognitive psychology—and its transition from a nonconstructivist to a constructivist vision of human cognition—came about when psychologists looked to education as a source of interesting problems to study. This self-correction in cognitive psychology was not achieved mainly through refinements of method and theory within psychology but rather through the challenge of understanding cognition that occurs in educational and other practical settings. When researchers shifted from studying lab animals in artificial contexts to studying humans in artificial contexts, psychology moved from its first to its second metaphor; similarly, when researchers shifted from studying humans in artificial contexts to studying humans in more realistic contexts, psychology moved from its second to its third metaphor.

FUTURE DIRECTIONS

The cognitive revolution that swept psychology in the 1960s proved to be remarkably resilient. Modern information-processing theory was born in the 1950s, as exemplified by Miller's (1956) rediscovery of limitations on short-term memory; organized in the 1960s, as exemplified in Neisser's (1967) and Atkinson and Shiffrin's (1968) descriptions of the human information-processing system; matured by the 1970s, as exemplified by Newell and Simon's (1972) computer simulation of human problem solving; and evolved toward constructivist theories by the 1980s and 1990s in light of the demands of explaining learning in real educational settings. From the vantage point of the mid-1990s, it appears that the continuing search for a metaphor of learning can lead educational researchers along two quite different paths—one based on science and one based on politics.

The Scientific Path

The three metaphors of psychology—including cognitive constructivism—all represent milestones along the scientific path. All are based on empirical research methods including both quantitative and qualitative methods. All use quantitative and qualitative data to test theories. The progression from response strengthening to information processing to cognitive constructing reflects progress in understanding human cognition.

Viewed from today's perspective, it can be seen that cognitive psychology not only overthrew behaviorism in the 1950s and 1960s but also successfully underwent a major shift of its own in the 1980s and 1990s. The forces that brought on the cognitive revolution included a desire for a broadened view of human cognition. This revolution was able to incorporate associationist concepts from its predecessor, as well as constructivist concepts that had lingered since its founding. There is reason to believe that it will be able to incorporate advances in emerging new areas. The cognitive approach to learning, including information processing, is not a doctrine but rather a continuing commitment to understand how the human mind works.

Although cognitive constructivism emerged as psychology's third metaphor, its predecessors still live in various forms, and several new forms of constructivism are currently vying for the position of psychology's fourth metaphor (Steffe & Gale, 1995). It seems likely that future metaphors will incorporate motivational and affective, social and cultural, and biological and physiological features. Will psychology continue to be able to assimilate and accommodate new ideas—as it did when it moved from information processing to cognitive construction—or will it be replaced by an entirely new approach? For those who take the scientific path, a likely scenario is that cognitive constructivism will continue to develop and grow in light of new research directions and will merge with other forms of constructivism.

The Critical Path

A more radical possibility is that the science of psychology will become irrelevant for education, with educational theorists looking instead to philosophical, political, and humanistic sources for its foundation. The critical path rejects science in general and psychology in particular, focusing instead on what Ernest (1995) described as "the critical paradigm, based on critical theory, and concerned to promote social justice and social change" (p. 463). Donmoyer (1993) articulated the premise of this conception: "Research always has political consequences" so educational researchers should "intentionally blur the distinction between research and political activity" (p. 41). It follows that educational research need no longer be based on testable theories and empirical data but rather can be based on opinions developed as "a process of critique or as a process of deliberation" (Donmoyer, p. 41).

The problem with this path is that it lacks a mechanism for self-correction. When theorists are freed from the pesky obligation to test theories against empirical data, all theories become equally valid. When educational practice once again is based on popular opinion rather than scientific evidence, the loudest voice is the one that is heard. I argued against taking an antiscientific path (Mayer, 1993):

> Within a scientific framework, the search for truth is guided not by those who develop the best slogans and ideologies but rather by those who can best explain the available data. In the words of Bronowski (1978, p. 1), 'there is a common sense of science' that allows for self-correction. In rejecting science in general—and, perhaps, psychology in particular—educational researchers would free themselves from the constraints of basing arguments on empirical data, from the need to distinguish between facts and opinions, and from excluding political agendas from research conclusions. To my way of thinking, however, rejection of these scientific values constitutes a conception of educational research that is demonstrably outmoded. (p. 6)

There is no place for educational psychology if one takes the critical path. This new conception of educational research "questions the authority traditionally accorded to 'behavioral science'" (Gergen, 1995, p. 27) and seeks to set educational practice based on doctrine. For example, Gergen stated, "from the constructivist standpoint, there is but limited educational gain to be derived from the traditional lecture format" (p. 31). Although the relative benefits of lecture formats and discussion formats could form the basis for research studies for those on the scientific path, no such studies are needed if educational practices are to be based solely on the degree to which they conform to a particular version of what is called "constructivist" doctrine. The issue is further complicated by the observation that all constructivists may not agree that little is to be gained from the lecture format, that is, there may not be agreement on how to derive the educational implications of constructivism. In short, the critical path turns constructivism into an ideology to which practice must conform rather than an evolving metaphor for explaining data and stimulating research.

Almost a century ago, educationally oriented psychologists held a vision in which psychology and education would contribute to one another (James, 1899/1958; Thorndike, 1906). Today, after decades of disappointment, this vision is finally on its way to becoming a reality. Psychologists have found that the challenges of education can be a source of revitalization for psychological theories; educators have found that psychologists are finally building theories that are relevant to educational practice. As educational psychologists continue their search for a metaphor of learning, prospects are high that the interaction of education and psychology will continue to bear fruit.

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