ABSTRACT: An issue that may prove especially worthy of investigation in the coming years is the relation between existing knowledge and learning. This article proposes five generalizations about existing knowledge, learning, and their interaction, and discusses evidence for these generalizations from recent research on children's learning, memory, conceptual understanding, and problem solving. Several of these generalizations address issues of longstanding concern in developmental psychology, such as why developmental sequences occur in the order that they do and why children sometimes fail to learn from seemingly reasonable instructional efforts. Others address issues that have received less extensive consideration, such as whether children's reasoning shows more consistency when they know little about concepts than when they know more about them. General benefits that may come from studying learning and existing knowledge in conjunction also are discussed.

Any history of the past 20 years of research on cognitive development would document two trends. First, there was a dramatic increase in the amount of research focusing on children's understanding of natural concepts such as time, space, morality, proportionality, conservation, and classification. More than 200 articles were published on conservation alone (Siegel, 1979). Second, in this same period, research on children's learning declined precipitously, Stevenson (in press) incisively reviewed this historical trend. He noted that few studies on children's learning were published until the 1950s, when more than 200 experimental studies appeared in journals. In the 1960s, more than 1,000 studies appeared. However, in the 1970s, far fewer studies of children's learning were published, and by 1980 "it was necessary to search with diligence to uncover any articles at all" (Stevenson, in press).

Many others agree with Stevenson's assessment of the contemporary state of research on children's learning. For example, Brown (1982) commented: Contemporary cognitive developmentalists, myself included, appear to go to extraordinary lengths to avoid using the word 'learning.' It is not merely a problem of elaborate symbol substitutions; we no longer seem to have an area called learning at all. (p. 187)

The demise of the study of learning is not unique to developmental psychology. As Voss (1978) noted, although the concept of learning may be found in cognitive psychology, it also must be conceded that the cognitive view of learning is vague, is abstract, and most important is lacking a substantive data base. (p. 13)

What caused this decline in studies of learning? Stevenson suggested two factors: the presence of charismatic figures such as Jean Piaget, who were not especially interested in learning and experimental data that were difficult to reconcile with existing learning theories. I believe a third factor also was important: the inexplicability of the basic assumption that learning mechanisms operate in the same way regardless of context and the mounting realization that people's learning and remembering are crucially affected by what they already know. Perhaps the seminal demonstration of this interdependence was Chi's (1979) finding that 10-year-old chess experts remembered more about the placement of chess pieces on a board than adult novice players, despite the adults' having considerably longer digit spans. The finding was exceedingly difficult to explain without postulating learning and memory mechanisms whose functioning was knowledge dependent. Yet traditional learning paradigms (e.g., transposition, reversal shift, paired associate learning) explicitly attempted to preclude knowledge more complex than interim associations acquired in the laboratory. Although there was little doubt that such classic learning mechanisms as stimulus generalization, discrimination, and extinction are used in complex knowledge domains, the ways in which they operated were far from obvious.

Fortunately, the seeds of a solution may be contained in the problem itself. In the course of studying existing knowledge of natural concepts, cognitive psychologists have developed a variety of methods for assessing conceptual understanding. These include double-assignment methodologies (Wilkinson, 1982), componential approaches (Stemberg & Riffkin, 1979), information integration approaches (Wilkening, Becker, & Tabasso, 1980), and rule as-
sesment approaches (Siegel, 1976). These meth-
ologies for assessing knowledge increase our po-
tential for studying learning as it interacts with knowledge. Indeed, this potential already is starting to be realized. Brown's (1982) and Voss's (1978) above-quoted lament about the decline of experi-
ments on learning are prefaces to their new efforts
to study the subject. In addition, Bowerman (1982),
Brown and Van Lehn (1982); Case (in press); Chi,
and Koensle (in press); Collins and Stevens (1982);
Fowler (1980); Jastebler, Sinclair, and Bovet (1974);
Kuhn and Phelps (in press); Strauss and Stave
(1982); and numerous other investigators have be-
gun to use assessments of existing knowledge to
study children's learning.

Recent research focusing on the interaction be-
tween existing knowledge and learning suggests that
at least five general conclusions. The three first gen-
eralizations concern aspects of children's existing
knowledge that are relevant to the study of learning
the fourth concerns the processes by which children
learn that their existing knowledge is inadequate,
and the fifth concerns the processes by which they
construct new rules to replace old inadequate ones.
Together, the generalizations suggest that studying
existing knowledge and learning in conjunction can
illuminate a number of issues of longstanding in-
teres among developmental psychologists as well as
raise new issues.

1. The rule is a useful basic unit for charac-
terizing children's knowledge. Which rules children
use can be assessed by designing problems that yield
distinct patterns of performance for different rules.

2. Children adopt premastery rules in the or-
der of their predictive accuracy, when accuracy is
controlled we have a range of environments at
which children apply the rules.

3. Children's reasoning across different con-
cept is more homogeneous when they have little
knowledge about the concept than when they have
more.

4. When children learn is determined in large
part by the interaction between their knowledge and
their environment. Children learn most efficiently
from experiences that indicate inadequacies in their
existing rules.

5. Once children have learned that their exist-
ing knowledge is imperfect, their encoding plays a
large role in constructing more advanced knowledge.

These generalizations provide a framework
within which to consider how studying the relation
between existing knowledge and learning can in-
crease our understanding of development. For each
generalization, one supporting example will be dis-
bussed in depth. These examples are drawn from
a series of experiments that Dean Richards and I per-
formed on the development of the concept of time.

By drawing all of the detailed illustrations from a
single research series, I hope to illuminate how the
generalizations relate to each other. In addition, a
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1. The role is a useful basic unit for charac-
terizing children's knowledge. Which rules children
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This use of the rule as a basic unit is far from unique to research on cognitive development. Research in linguistics (e.g., Chomsky, 1957), computer science (e.g., Lenat, 1977), instructional psychology (e.g., Collins & Stevens, 1982), and adult cognitive psychology (e.g., Levine, 1966) also has adopted the rule as a central unit of analysis.

The prevalence of theories that emphasize rule use has placed a premium on methodologies for identifying which rules people employ. Some of the most dramatic evidence for rule use has come from analyses of errors. Klima and Bellugi-Klima (1966) quoted children's speech errors in ways that compellingly illustrated the children's imperfect rules for producing negations and wh questions. Levine (1966) demonstrated how patterns of errors and correct answers could be used to identify people's hypotheses on artificial concept-formation problems. More recently, I have extended these error analysis approaches to a wide range of conceptual development and problem-solving tasks. The essence of the rule assessment approach that I developed for this purpose is to generate rules that people might use and then to formulate problem types that yield a distinct pattern of answers for people using each rule. To date, my colleagues and I have applied this strategy to identify children's rules on 13 tasks: balance scale, projection of shadows, probability, fullness, conservation of liquid quantity, conservation of solid quantity, conservation of number, counting of objects, Tower of Hanoi, animacy, speed, time, and distance (Klahr & Robinson, 1981; Siegler, 1976, 1981; Siegler & Klahr, 1982; Siegler & Richards, 1979; Siegler & Vago, 1978; Brain & Siegler, Note 1; Richards, Note 2).

To illustrate how the rule assessment approach works, we can examine its application to three concepts that are of interest for both theoretical and practical reasons: the concepts of time, speed, and distance. Developmental research on these concepts has a picturesque history. In 1928, Albert Einstein attended a lecture given by Jean Piaget. At the end of the lecture, Einstein posed a question: In what order do children acquire the concepts of time and speed? Almost 20 years later, Piaget published a two-volume, 500-page reply to Einstein's query (Piaget, 1946/1969, 1946/1970). In essence, Piaget claimed that children understand time and speed simultaneously, at roughly age seven, and that the two concepts develop from a common ancestor, a rudimentary spatial concept. However, a number of methodological questions have made it difficult to evaluate Piaget's claims (cf. Weinreich & Brainerd, 1975). To overcome these objections, Siegler and Richards (1979) applied the rule assessment approach to measuring children's understanding of time, speed, and also distance. The task was similar to Piaget's (1946/1969) cars task. Children were shown two parallel electric-train tracks, each with a locomotive on it. The locomotives' activities could vary along seven dimensions. The trains could start at the same or different points, stop at the same or different points, and travel the same or different distances. They could start at the same or different times, stop at the same or different times, and travel for the same or different total times. Finally, they could travel at the same or different speeds. Children were asked which train traveled for the greater time, for the longer distance, or at the faster speed.

On the basis of Piaget's (1946/1969) descriptions and our own task analyses, we expected children to use one of three rules on this task. Rule 1 children would base their judgments on the locomotives' end points; whichever train stopped farther would be said to have traveled for the longer time, for the greater distance, or at the faster speed. If the trains stopped at the same point, children would conclude that they traveled for the same time, for the same distance, or at the same speed. Rule 2 children would make the same judgments if the trains stopped at different points, but would choose the train that started farther back if the trains stopped at the same point. Rule 3 children would judge each concept in terms of the appropriate dimensions; time would be judged in terms of starting and stopping times, distance in terms of beginning and end points, and speed in terms of distance traveled per unit of time.

To test for use of these hypothesized rules, it was necessary to formulate problems that would yield distinct patterns for children using different rules. The six problem types that we devised are shown in Table 1. In the diagram at the top of the table, the lengths of the lines correspond to the relative distances traveled by the two trains. The leftmost ends of the lines correspond to the starting points and the rightmost ends to the stopping points. The numbers refer to the starting and stopping times of each train (in seconds after the onset of the trial). The letter "I" indicates which train traveled faster. Thus, in the problem-type 1 example in Table 1, the trains started at the same relative points on their tracks; and Train A finished farther up the track; Train A therefore traveled the longer distance. Train A started earlier than Train B, and they stopped at the same moment; therefore Train A traveled the longer time. Train B traveled at the faster speed. The bottom of Table 1 presents the pattern of answers that would be generated if children following various rules were asked which train traveled the longer time, the farther distance, or which child consistently bowed the end point rule (Rule 1) would solve 100% of items of problem-types 1, 3, and 5 but 4% of types 2, 4, and 6.

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These problem-types allowed us to assess what role a child used. For a child to be classified as using a particular rule, at least 80% of his or her responses had to be in accord with the predictions of that rule. Because there were three possible responses (Train A is greater, Train B is greater, they are equal), the rules had to predict not only which items would be solved correctly but also the particular errors that children would make.

In our first experiment on children's understanding of time, speed, and distance, 5-year-olds, 8-year-olds, 11-year-olds, and adults were presented four examples of each of the six problem-types shown in Table 1. The trains' activities were identical on the items testing knowledge of each concept; the only difference was whether the experimenter's question concerned time, speed, or distance (cf. Siegler & Richards, 1979, for methodological details).

Most participants met the criterion for using a rule on each concept. On all three concepts, most 5-year-olds used the end point rule. That is, they said that the train that stopped at the more advanced point on the track was the one that had traveled faster, for the greater amount of time, and for the longer distance. At the other end of the age spectrum, almost all adults judged each concept in terms of the appropriate dimension. The 9- and 11-year-olds' performance was less homogeneous. On the distance and speed concepts, most of them used the correct rule. On the time concept, however, many of them did not meet the criterion for using any rule, and those who did most often used a rule that had not been anticipated. The distance rule. That is, they consistently said that the train that went the farther distance was the one that had traveled for the greater time. We performed regression analyses of the distribution of errors of the "no rule" children, most of whom were 5- and 11-year-olds. These children, too, tended toward using the distance rule on the time concept; 67% of the variance in their number of errors on the 24 problems was accounted for by the prediction that children would err on those problems in which the train that traveled the larger distance did not travel for the longer time. One consequence of this rule sequence was that performance on problem-type 3 of Table 1 actually declined with age. Five-year-olds, most of whom used the end-point rule (which predicts accurately on this problem) were correct on 71% of the trials. Eleven-year-olds, who tended to use the distance rule (which predicts inaccurately on this problem) were correct on only 27%.

There are several points to note about this rule assessment method. First, the rule models predict not only whether children will answer each question correctly or incorrectly, but also the particular errors they will make. Second, the basic level of data analysis is the individual child rather than an age group. Third, the method allows detection of alternative rules that are not initially hypothesized. For example, we did not initially hypothesize that children would use the distance rule on the time concept, but we detected it because a number of children showed the same pattern of answers.

A number of other investigators have developed related assessment methodologies, in which they used patterns of errors or reaction times to infer...
individual children's rules. Consider the area of arithmetic, for example. Groen and Renwick (1977) analyzed patterns of solution times to determine preschoolers' addition rules. Riley, Greeno, and Helrt (in press) analyzed patterns of errors in children's representations of addition word problems and derived three rules by which young children interpret such problems. Brown and Burton (1978) analyzed patterns of errors on multidigit subtraction problems and derived a variety of "bugs" subtraction rules, that is, substitution rules that differ from the standard correct one or result in one or more "bugs." Numerous other examples of approaches for determining children's rules could be drawn from Piagetians, academic, and classic problem-solving tasks (e.g., Case, 1978; Klahr & Robinson, 1981; Sternberg & Ristkin, 1979; Strauss & Slav, 1983).

Although many researchers agree that the rule is a useful basic unit of analysis, there is less agreement on the optimal method for measuring rule use. For example, some researchers have voiced concerns about the rule assessment approach. Willeneng and Anderson (1982) wrote that "the decision tree methodology is unable to assess algebraic integration rules" (p. 215). This comment raises the issue of whether there is an inherent link between the use of decision trees and the rule assessment methodology, and also whether the rule assessment approach can detect the use of algebraic integration rules. The phrase "decision tree methodology" reveals one confusion. Decision trees are a language in which rules can be expressed; they are not a methodology. The rule assessment methodology has been used to examine the use of rules expressed as decision trees, flow diagrams (Siegel & Vago, 1978), and production systems (Klahr & Sigler, 1978). It has also been used with rules expressed in part as algebraic formulas (Rule 4 in Siegel, 1976). Beyond this specific confusion of languages for expressing rules and methodologies for detecting them, there is the general issue of the range of rules that the rule assessments approach can detect. Wilkening and Anderson (1987) claim that the rule assessment approach cannot detect algebraic integration rules. For example, they claim that if children are presented a balance scale with a fulcrum in the middle and weight on pegs on each side of the fulcrum, and asked to predict which side will go down, that the rule assessment approach could not detect their use of rules such as "two weights times distance equals torque," or "two weights plus distance equals torque." This claim is simply incorrect. For example, to discriminate between these two integration rules, we could present children problems such as three weights on the first peg on the left side of the fulcrum versus one weight on the fourth peg or the right.

Children using the first rule would say the right side will go down; children using the second would say that the left side will. If we wanted to discriminate among additional integration rules, we could add more problem types for which the rules would predict differently. In contrast, since the functional measurement approach assumes that rules will be an algebraic combination of the systematically manipulated dimensions, the rules it can detect are limited. If a functional measurement experiment on number conservation varied the length and density of the rows of objects, it would discover that 10-year-olds' performance fit a "length times density" equation, even if their judgments in fact were generated by reliance on the type of transformation performed (Siegel, 1981).

The stage of determinate rules that can be detected by the rule assessment approach is limited only by the particular problems that are presented. These, of course, are constrained to an extent by the investigator's initial hypotheses about what rules people will use, but this is true of the information integration approach, the rule assessment approach, and any scientific methodology. It is more pertinent whether the assessment approach can distinguish among specific rules that have been hypothesized to represent people's knowledge. The rule assessment approach seems well suited to this task.

A second, related concern has been that the methodology restricts the possible behaviors that children can produce, and that these restrictions are responsible for the rules that children are classified as using. Strauss and Levin (1981) pointed to three restrictive ways in which tasks typically have been presented: The tasks are presented in a fixed fashion; there are only a few response alternatives, and children's justifications are not considered in the rule assessments. Although these descriptions accurately characterize my use of the rule assessment approach, applications by other researchers demonstrate that none of them is inherent to the methodology. Klahr and Robinson (1981) applied the rule assessment approach to a Tower of Hanoi task, using an open-ended procedure that included the active involvement of children in setting up the problems. Brown and Burton's (1978) work on subtraction strategies allowed the entire range of numbers as possible responses. Richards and Siegel (Note 3) applied the rule assessment approach to children's explanations of what attributes make an object alive. The only essential aspects of the rule assessment approach are that the rules formulated lead to unambiguous predictions on particular problems and that the problem types discriminate the hypothesized rules from each other.

These points of disagreement should not obscure several points of basic agreement that underlie...
all of the approaches. All of the investigators agree that the rule is a useful basic unit for characterizing cognitive activity. All agree that the optimal level of data analysis is the level of individual children's knowledge. They also agree that to determine what rule people are using, one should present problems on which people using different rules will respond differently. We disagree on whether continuous measurement or discrete judgment procedures are the most desirable, on the degree to which children should actively participate in setting up problems, and on the usefulness of verbal explanations as data. Determining how best to assess people's rules promises to be a lively issue in the coming years.

2. Children adopt prematurity rules in the order of their predictive accuracy, when accuracy is considered across the range of environments in which children apply the rules. An invariant developmental sequence of knowledge states has prima facie relevance for the study of learning; it immediately raises the issue of what acquisition process produces such a regular sequence. Flavell (1972) distinguished three sources that could produce invariant sequences: the structure of the task, the structure of the environment, and the structure of the child. He suggested that investigators first try to explain invariant sequences as resulting from the structure of the task, since this explanation most often would prove applicable. If the structure of the task did not provide a satisfactory explanation, the investigator should consider the structure of the environment, the next most likely explanation. If both of these failed, the structure of the child should be considered.

Recent cognitive developmental theories can be classified in the terms of Flavell's taxonomy. Bruner's (1975), Carse's (1978), and Fischer's (1980) theories have emphasized the structure of the task (or, more precisely, the structure of the rules used to perform the task). Chi and Rees (in press) and Carey (in press) have emphasized the order in which the environment provides opportunities to acquire knowledge. Keil (1981) and Wexler, Culican, and Hamburger (1979) have contended that constraints inherent to human children, as well as the structure of the domain of knowledge, govern the order in which natural concepts are acquired.

In seeking to explain invariant sequences, it may be useful to distinguish between-concept sequences from within-concept sequences. Between-concept sequences involve the ordering of different concepts; for example, children always might understand speed before they understand time. Within-concept sequences involve the progression from one rule to another on a single concept; for example, children first might use the end point rule on the most concept task and later the distance rule.

Explanations that emphasize the structure of the environment and of the child may well prove to provide the most compelling explanations for between-concept sequences. Almost all explanations of within-concept sequences, however, have emphasized the structure of the rules that are used on the task. Researchers have proposed several hypotheses for how the structure of the rules might produce invariant within-concept sequences. The most frequently advanced hypothesis is that such sequences arise because earlier-developing rules are included in later-developing ones (Fischer, 1980; Flavell, 1972; Flavell & Vohvill, 1969; Gagné, 1968). This explanation seems plausible for many within-concept sequences, but not for all of them. For example, on the time task, neither the end point rule nor the distance rule is linked by any inclusion relation to the time rule. Yet the time rule is based on information about beginning and ending times, whereas use of the end point and distance rules is based on information concerning spatial relations. Similarly, Siegler (1981) found that on tasks involving conservation of liquid and solid quantity, children first used rules based on length or height and later shifted to rules based on the type of transformation that was performed. Again, no inclusion relation between the dimensions is obvious.

An alternative explanation is that children's prematurity rules are ordered by their relative predictive accuracies in the range of environments in which the children apply the rules. This view can be evaluated only if we specify both the rules that children use and the range of environments in which they apply them.

The Siegler and Richards (1975) study on the time concept provides an illustration. Given a set of randomly chosen problems involving trains moving in the same direction on parallel tracks, there almost always will be a positive relation between which train stops further down the track and the train that travels for the longer time. If the two trains travel at the same speed and begin at the same point the relation is guaranteed. However, distance traveled will more accurately predict which train travels for the longer time. Only the speeds of the two trains need to be equal to guarantee that the train that travels the longer distance also will have traveled the longer time. Thus, if children use both the end point, and the distance rules to judge travel time at different points in development, they should proceed from the end point to the distance rule, rather than the reverse.

What process leads children to adopt more predictively accurate rules and to reject less accurate ones? Klahr and Wallace (1976) described one inductive mechanism that could have this effect. They suggested that people maintain in memory a time
line, a record of their hypotheses and the outcomes associated with each. When the predictive accuracy of a hypothesis exceeds some minimum critical consistency level, they adopt the hypothesis as their rule. They then might reset the critical consistency level to the predictive accuracy associated with the rule. If the critical consistency level of a child's current rule was below perfect predictivity, the child period- ically might try other hypotheses to obtain data on how well they predicted. If a new hypothesis was arbitrarily predicted more accurately than the current rule, the child would adopt the rehypothesis as his or her rule and reset the critical consistency level to the higher point. Note that this mechanism does not imply that all children progress through the same invariant sequence, since a variety of rules may predict more accurately than the existing one. Rather, the view suggests that if a child ever uses a given pair of rules to solve a problem, he or she will do so in an invariant order (cf. Fischer, 1980, for a related view).

Within the view that permanency rules are ordered by their relative predictive accuracies in the task environments in which they are used, inclusion relations emerge simply as a special case. In such inclusion relations, the more advanced rule solves all of the problems solved by the less advanced rule and all others as well. For example, Rule 2 on the balance scale (consider weight in all cases and also consider distance when weights are equal) must follow rather than precede Rule 1 (consider weight in all cases), because Rule 2 predicts correctly on every problem that Rule 1 does and on some other problems as well. Such inclusion relations are plentiful for researchers to work with, since they obviate the messy issue of specifying the task environment to which the rules apply. However, many consistent within-concept sequences appear to exist without an inclusion relation; exploring the bases of these does require specifying the domain to which the rules are applied.

The emphasis on considering the total domain of problems to which a rule is applied suggests a simple explanation for a phenomenon of considerable recent interest among developmentalists—that of U-shaped curves. U-shaped curves are data patterns in which children first perform well on a task, then less well, and then well again. At first, such patterns appear quite mysterious. There exists a sim- ple explanation for them, however. U-shaped curves arise when children adopt a new rule that is more predictive when the total task environment is considered but that is less predictive in a particular portion of the task environment. To illustrate, on problem-type 3 of the time concept problems described above, 5-year-olds solved 71% of items, 11-year-olds 27%, and adults 81%. Recall that the distance rule that many 11-year-olds used was in general a better predictor of travel time than the end point rule used by 5-year-olds. On problem-type 3, however, relying on end-point cues led to correct answers, whereas relying on distance cues led to incorrect ones, thus accounting for the 5-year-old's greater percentage of correct answers (Riegle & Siegler, 1981). It can be con- stricted that this explanation accounted for U-shaped curves not only in rule assessment studies but also in several other sorts of tasks that involve the finding of such data patterns: Cazden's (1968) data on morphological rules, Weir's (1964) data on probability learning, Mehlber and Levee's (1967) data on number conservation, and Gardner, Kitchner, Win- ner, and Perkins' (1974) data on metaphor (see Strauss and Stavy, 1982) for a different view on the origins of U-shaped curves.

3. Children's reasoning across different concepts is more homogeneous when they have little knowledge about the concepts than when they have more. If existing knowledge and learning are related, then the broader the consistency of children's reasoning, the more encompassing the predictions that cognitive developmentalists might make about learning. It therefore seems worthwhile to search for consistent reasoning patterns that may exist in some domains of knowledge, at some points in processing, and at some levels of conceptual understanding, even if development is not in general stage-like (cf. Flavell, 1982).

Fischer's (1980) theory of cognitive development is representative in two ways of many researchers' current views on the developmental synchrony issue. First, he concluded that "unreliability is the rule in development" (p. 310). Broad consis- tencies in reasoning, such as those envisioned by Piaget's and Kohlberg's stage theories have rarely been found. Second, even researchers who, like Fischer, have become pessimistic about the existence of synchronies remain interested in finding them. In the same article in which he concluded that unreliability was the rule in development, Fischer pro- posed that limited information-processing capacity might result in a kind of homogeneity of reasoning, as all of a child's highest accomplishments would be at a certain level of processing complexity (cf. Case, in press, and Flavell, 1982, for similar sug- gestions).

Another place where cognitive developmentalists might look for consistent reasoning across concepts is in children's pragmatic rules. The results of a number of experiments using the rule assessment approach have indicated that young children approach some quite diverse tasks in the same way. Figure 5 illustrates how great this similarity was for 5-year-olds who were presented parallel problem- types to assess understanding of three conservation

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and three proportionality tasks. On four of the six tasks, almost all of the 5-year-olds based their predictions on a unidimensional rule, and on a fifth task most of them did. In predicting a balance scale’s behavior, the 5-year-olds said that the side of the fulcrum with more weight would go down; in predicting the workings of a shadows projection apparatus, they said that the larger object would cast the larger shadow; on a probability task, they said that the pile of marbles with the greater number of desired-color marbles would be more likely to yield a desired-color marble (regardless of the number of undesired-color marbles in each pile); on a liquid quantity conservation task, they judged the glass with the taller liquid column to contain more water; on a solid quantity conservation task, they judged the longer piece of clay to have more clay. Sigler and Richards (1979) reported that 5-year-olds used similar rules on time, speed, and distance tasks (the train that stops farther up the track has traveled for a greater time, at a higher speed, and for more distance). Sigler and Vago (1978) obtained similar results for a fullness task (the glass with the taller liquid column is more full), as did Richards (Note 2) on an animacy task (if and only if an object is an animal, it is alive).

![Figure 1](image)

**Figure 1 Five-Year-Olds’ Performance on Six Problem-Solving Tasks**

### Balance Score

- **Liquid Quantity Conservation**
  - E 5 S C E C E
  - 50 60 70 80 90 100
- **Solid Quantity Conservation**
  - E 5 S C E C E
  - 30 40 50 60 70 80
- **Number Conservation**
  - E S D C E C E
  - 30 40 50 60 70 80

### Size of Shadows

- **Recognition of Shadows**
  - E 5 S C E C E
  - 0 10 20 30 40 50
- **Probability**
  - E 5 S C E C E
  - 0 10 20 30 40 50

### Why might such consistency of reasoning appear? One explanation involves fall-back rules. That is, people may have certain standards forms of reasoning on which they rely when they lack detailed procedures for solving a problem. Five-year-olds may utilize a fall-back rule of the following form: If you lack direct information about how to solve a problem on which you are to make a quantitative comparison, it is best to compare the values of the single, seemingly most important dimension and to choose the object with the greater value on that dimension as having more of whatever dimension is being asked about.

Conceptualizing young children’s unidimensional approaches as reflecting fall-back rules, as opposed to capacity limitations, suggests reasons why such approaches are observed in some but not all situations. Piagetian tasks seem ideal for revealing fall-back rules. One criterion that Piaget used to select his tasks was that they not be familiar to children; he was less interested in the facts that they might know than in their reasoning in the absence of specific knowledge (Piaget, 1972). In a sense, he was interested in the children’s fall-back rules. Problems selected by other criteria, such as ecological validity, would be less likely to reveal fall-back rules, since children might have developed specific procedures for dealing with them. Even task variants that place Piagetian problems in familiar contexts might obscure children’s fall-back rules if the familiar contexts suggest specific content-based approaches for children to use.

Case (Note 4) formulated descriptions of horizontal structure in children’s thinking that were similar to the Siegler (1981) fall-back rules both in their general kind and in their specifics. Case’s description of the underlying structure of 5- and 6-year-olds’ thinking was as follows:

> Given the requirement for making a quantity judgment along DIMENSION X, set yourself the subgoal of making a judgment of relative quantity along DIMENSION Y. Then use the result obtained to make a decision about X. (p. 10)

Case cited evidence from research on young children’s concepts of justice, happiness, proportionality, and success to illustrate the use of unidimensional approaches. Strauss and Stavy (1982) observed similar reasoning on the concepts of time, sweetness, and temperature. They suggested that it reflected 5- and 6-year-olds’ tendency to rely on direct function logic.

Case’s notion of horizontal structure rules, Strauss and Stavy’s (1982) notion of direct function logic, and my notion of fall-back rules suggest a number of questions. Do children older than 5 or 6 years possess some analogous standardized procedure for dealing with newly encountered complex situations? If so, is it the same procedure as that used by 5- and 6-year-olds or a different one? Finally, do children use such approaches to reduce memory load, to check whether the simplest plausible solution works, to determine whether a frequently useful analogy can be extended to the new situation, or for some other reason? Each of these issues seems worthy of future research.

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4. When children learn is determined in large part by the interaction between their knowledge and their experience. Children learn most efficiently from experiences that indicate inadequacies in their existing rules. Predicting the conditions under which children learn has been a longstanding goal of cognitive developmentalists. Such venerable constructs as readiness (Flure, 1908), critical periods (Riesen, 1947), the problem of the match (Hunt, 1961), behavioral prerequisites (Gagné, 1966), and aptitude-treatment interactions (Cronbach & Snow, 1977) all can be seen as efforts to predict which people will learn and when they will learn. Differential learning as a function of age, stage, and knowledge has been predicted by stage theories (Piaget, 1972), behavioral theories (Gagné, 1968), and psychometric theories (Guilford, 1967) alike.

One reason why instruction might have different effects on different children is that the instructional procedure could reveal some deficiencies in existing knowledge and not others. By assessing children's initial rules and by viewing instructional experiences in relation to those rules, we can anticipate which experiences will benefit children. This view implies that instructional procedures are not effective or ineffective in an absolute sense. Their effectiveness depends on their relation to the learner's knowledge.

Research on the time concept illustrates this point. Siegler and Richards (Note 5; see also Richards, 1983) presented a test to identify 5-year-olds who used the end point rule and 11-year-olds who used the distance rule to judge time. The test presented to each child one of the four types of feedback problems shown in Figure 2. These problems differed in whether they discriminated the distance rule, the end point rule, both, or neither from the time rule. For example, distance-discriminating problems (problem-type B in Figure 2) did not discriminate the end point rule from the time rule, since children answering on the basis of end points always would be correct. These children would have little reason to believe that their existing knowledge was imperfect. On the other hand, children using the distance rule would learn that their existing approach was inadequate, since their answers would elicit the comment "No, the other train traveled for the longer time." Since 5-year-olds were selected for relying on the end point rule and 11-year-olds for relying on the distance rule, we anticipated that feedback problems that discriminated end points but not distances from time would help younger children but not older ones, whereas problems that discriminated distances but not end points from time would help older children but not younger ones.

The results supported these predictions. They also revealed how children's performance could mislead teachers into thinking that children understood concepts when in fact they did not. Consider the performance of 5-year-olds who were given the distance-discriminating problems. As shown in Figure 3, these children did very well on the feedback problems, better than the 11-year-olds on all trial blocks. However, their high percentage of correct answers masked the fact that they were not learning anything. On the posttest, 70% of them used the same end point rule with which they started. In contrast, only 15% of the 5-year-olds who received problems that discriminated end points from total times continued to use the end point rule on the posttest. A similar pattern emerged with the 11-year-olds: 55% of those who saw distance discriminated from

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**Figure 2**

**Problem Types Used in Time-Learning Study**

A. Discriminates End Point

<table>
<thead>
<tr>
<th>0^*</th>
<th>3^*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^*</td>
<td>1</td>
</tr>
<tr>
<td>6^*</td>
<td></td>
</tr>
</tbody>
</table>

B. Discriminates Distance

<table>
<thead>
<tr>
<th>0^*</th>
<th>6^*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^*</td>
<td>1</td>
</tr>
<tr>
<td>5^*</td>
<td></td>
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</tbody>
</table>

C. Discriminates Distance and End Point

<table>
<thead>
<tr>
<th>0^*</th>
<th>4^*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3^*</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>6^*</td>
</tr>
</tbody>
</table>

D. Discriminates Neither End Point

<table>
<thead>
<tr>
<th>Not Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^*</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>6^*</td>
</tr>
</tbody>
</table>

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time advanced to the time rule on the posttest, versus 20% of those whose feedback problems did not discriminant between the two dimensions. Without (a) knowledge of the children’s initial rules and (b) classification of the feedback problems relative to those rules, it would have been difficult to predict which of the feedback problems would help which children to learn.

Efforts to fit instructional techniques to learners’ knowledge extend far beyond simple feedback procedures and elementary physics problems. In one striking report, Cohen and Stevens (1982) documented the ways in which expert teachers adjust their questions, examples, and hypothetical cases to address shortcomings of their students’ existing knowledge. Many of their illustrations were drawn from efforts to teach students about the conditions under which rice can grow. Students who thought high rainfall was necessary were confronted with positive counterexamples, such as Egypt, where there is little rainfall but much water due to irrigation. Students who did not realize that warm temperature was necessary were presented with negative counterexamples, such as Oregon, which has many prerequisites for rice growing but is not warm enough. Students who knew that large quantities of water and warm temperatures were important for growing rice, but who did not realize the importance of soil quality, would be queried, “Then they grow rice in Florida?”

Collins and Stevens (1982) also observed that expert teachers have priorities that guide their decisions concerning which aspects of students’ knowledge to try to improve first. They correct errors before omissions, because erroneous ideas interfere more seriously with acquisition of new information.

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They also correct mistaken ideas about factors that arise earlier in causal chains before mistaken ideas about factors that arise later, for much the same reason. The efficacy of such instructional priorities seems well worth testing; if learning arises from an interaction between existing knowledge and newly presented information, then it becomes important to determine which limitations of existing knowledge instruction should focus on first.

Some investigators have questioned whether existing knowledge is in fact related to learning. For example, Brainerd (1977, 1978) examined the conservation-training literature, argued that studies that claimed to have demonstrated a link between knowledge and learning conflated their measures of learning with existing knowledge, and performed a new analysis that did not reveal such a link. He concluded that "experimenters have failed to show that children learn better when they know a little bit about an object than when they know nothing at all" (Brainerd, 1978, p. 191).

From the present perspective, which views learning as arising from the interaction of existing knowledge and new experience, it seems more profitable to ask how the experience relates to the knowledge than to ask whether initially more knowledgeable children learn faster or slower. Depending on the ec between the existing knowledge and the instructional procedure, existing knowledge can be positively related, negatively related, or unrelated to the amount of learning. Recall the results of the time-learning experiment. Given feedback on the distance-discriminating problems, the initially more knowledgeable children (those who used the distance rule) learned more; the same was true on the end-point discriminating problems, the initially less knowledgeable children (those who used the end point rule) learned more. Learning and knowledge were clearly related, but the relation was more complex than a certain amount of existing knowledge leading to a certain amount of learning. Instead, the interaction between knowledge and learning was crucial.

5. One children have learned that their existing knowledge is imperfect, encoding plays a large role in their construction of more advanced knowledge. Experiences that confirm children's existing rules may begin the learning process, but they do not complete it. Once existing rules are disconfirmed, children still must formulate new ones. A number of findings suggest that encoding is a critical component in the process by which new rules are formed.

Encoding is the process by which stimuli are represented in a particular situation. An encoding of a stimulus is not always identical to a person's representation of the stimulus in long-term memory. Portions of the encoding may be created at the time the stimulus is presented. For example, Pellegrino and Glaser (1982) presented college students the analogy 15:19 :: 6:12 :: ? It seems unlikely that college students' representations of the number 19 in long-term memory included the property "is more than 15" prior to the presentation of this problem. In this task situation, however, 19 probably is encoded in this way. Complementarily, relevant information (e.g., long-term memory may be omitted from a particular encoding. Sternberg (1977) presented the analogy problem, Washington 1 :: Lincoln 2 :: (a) 10 or (b) 5. This problem is difficult because the relevant information is absent from long-term memory (Whose faces are on $1 and $5 bills?), but rather because the relevant information is not included in most people's encoding of the problem.

Research from a variety of disciplines documents the role of encoding. For example, investigations of expertise in such areas as chess (Chase & Simon, 1973), go (Retman, 1976), physics (Chi, Glaser, & Rees, 1982), and radiology (Leighton, Felton, Glaser, & Wang. Note 6) indicate that the features that experts encode differ noticeably from those which less knowledgeable individuals encode. In children's cognitive development, however, encoding skills may play an especially large role. Across a wide range of situations, children are less likely to know which aspects of the stimuli should be encoded in a particular situation, and their long-term memory representations of the stimuli are likely to be less rich. That children lack knowledge about what to encode may account for the seemingly conflicting claims that young children's concepts are holistic, underspecified, and overly general, as well as particularistic, exemplar based, and overly specific (Bruner, Oliver, & Greenfield, 1966; Clark, 1973; Fausten, Fausten, & Tally, 1982; Nelson, 1973; Vygotsky, 1934; Werren, 1948).

Encoding that is less than optimal may constrain children's ability to learn and also may influence the form that learning takes. Bransford (1979) provided the following illustration of how inadequate encoding can interfere with learning.

Imagine that a speaker says, "Notice the sepia," while pointing to a complete painting. Unless you know that sepia refers to a color (and more specifically, to a brownish color), you will have difficulty understanding what the speaker means. Wittgenstein suggests that even learning by ostensive definition (for example, hearing, "This is red" while showing someone point to a red object) presupposes that one has some knowledge of what the ostensibly defined object is supposed to be an example of (in this case color). Knowledge that a word refers to the category "color" affects one's understanding of the object of the pointing gesture, which in turn may increase one's understanding of what sepia is at red. (p. 222)
Anotic experiment in the Siegel and Richards (Note 5) study of the time concept empirically demonstrates the role of encoding in learning. Recall that only one-half of the 11-year-olds who received feedback problems that discriminated their existing distance rule from the time rule adopted the time rule for solving temporal comparison problems. To develop hypotheses about why the other half did not do so, we performed a task analysis of the time problem. Given that the two trains always either started or stopped at the same time, children could execute the time rule by first encoding relative starting times (which train started first or whether the trains started simultaneously), then encoding relative stopping times (which train stopped last or whether the trains stopped simultaneously), and then inserting the encoded values into one of two inference rules: if two or more events start at the same time and one stops later than the other(s), the event that stopped last took the longest time; if two or more events start at different times and they stop at the same time, the event that started first took the longest time. This analysis suggested that children’s difficulty in learning might stem either from not encoding the appropriate information about starting and stopping times or from not using appropriate inference rules.

To examine these possibilities, we developed means of assessing encoding and inference precises independent of children’s comparisons of time. Encoding was assessed by presenting the 11-year-olds participants the usual train problems, but mixing in questions about which train started first and which train stopped last along with the usual questions about which train traveled for the greater time. Inferences were assessed by telling children the order in which the trains started and stopped, thus obviating encoding problems, and asking them to infer which train traveled the greater time. These assessments indicated that both precises were plausible sources of the children’s difficulty in learning the original temporal-comparison problems. Children did not consistently encode the temporal features; they frequently erred in indicating the order in which the trains started and stopped. Even when they were told which train started first and which train stopped last, they often did not draw the correct inference about total times.

We further probed these potential sources of difficulty by training a new group of 11-year-olds in the appropriate inferences, encoding, or both. Encoding instruction involved telling the subjects to identify aloud at the beginning of each trial the train that started first (or to say that the trains started at the same time) and to identify aloud at the end of each trial the train that stopped last (or to say that they stopped at the same time). Inference training involved telling children the solutions to the problems previously used to test knowledge of inference rules and repeating the questions until they could answer them correctly.

The inference training by itself had little effect on encoding or on judgments of total time. However, the instruction in both encoding and inference led to improvements in both encoding and judgments of total time. Whereas only about one-third of children given inference instruction alone could be classified as using the time rule, more than 90% of those given instruction in both encoding and inference adopted it. Thus, changing the features that children encoded allowed them to learn from a more direct instructional procedure.

Several investigators have suggested mechanisms by which changes in encoding might influence learning. Holland and Reitman (Note 7) illustrated how a process similar to biological evolution might operate. Their model of the learner’s knowledge was a set of condition-action pairings much like a production system. Each production included a string of 1’s and 0’s on the condition side (the system’s encoding of the environment) and another string of 1’s and 0’s on the action side (the response the system would make, given that encoding). Each production also was associated more or less strongly with attainment of the system’s goal; these associations grew in strength as the production fired as part of a sequence that led to goal attainment. Periodically, two productions with different sequences on the condition side but the same sequence on the action side were selected to be “parent productions.” For example, two parent productions might be 010 → 010 and 000 → 010. The more highly associated with goal attainment a production was, the more likely it was to be chosen as a parent production. New productions were generated by making an arbitrary cut at corresponding positions on the condition sides of the two parent productions and then combining symbols to the left of the cut in one production with symbols to the right of the cut in the other. This created productions with new encodings of the environment. In the above two productions, making a cut between the second and third position on the condition side would give birth to the productions: 001 → 010 and 100 → 010. One of these new productions would be chosen arbitrarily for inclusion in the production system and would replace a production that was weakly associated with goal attainment. Holland and Reitman reported that this mechanism for creating new encodings greatly increased the efficiency with which their model learned in an artificial environment. The mechanism also allowed the model to learn in a new environment in which it had no direct experience.

In Langley’s (1981) BACON.3 program, new
The study of learning can also increase confidence in hypothesized developmental sequences. Observing what rule children move toward when their existing rule is disconfirmed can be especially helpful. Again using the time concept to illustrate, 5-year-olds who saw the end point rule disconfirmed by feedback problems moved onward the distance rule. These children could have adopted the time rule, which was equally consistent with the feedback problems, but they did not. The fact that they adopted the distance rule rather than the time rule or some other approach strengthened our belief that children usually progress from the end point rule to the distance rule to the time rule.

Finally, the broadened assessments of existing knowledge that can result from experiments on learning can in turn broaden our perspective on how children learn. If we had not known that 11-year-olds had difficulty learning the time rule even when they were given distance-discriminating feedback problems, we would have been unlikely to assess their encoding. If we had not known that they did not encode beginning and ending times very accurately, it is unlikely that we would have attempted to influence their learning by telling them to name aloud the train that started first and the one that stopped last. Here again, the study of existing knowledge and learning proved to be mutually supportive. It seems that, in general, the broader and more precise our assessment of existing knowledge, the more we can discover about learning, the broader and more precise our understanding of learning, the more we can discover about existing knowledge.

REFERENCE NOTES

REFERENCES
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