Microdevelopment

Transition Processes in Development and Learning

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1 Microgenetic studies of self-explanation

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Microgenetic methods are useful for many purposes. They can yield more precise descriptions of cognitive change than would otherwise be possible, can reveal both similarities and dissimilarities in change processes across tasks and age groups, and can provide the type of detailed data that are essential for constructing formal models of cognitive change. Further, as is amply demonstrated in this volume, they are useful for examining change involving a wide variety of tasks and age groups and for addressing a wide variety of theoretical issues.

In the present chapter, I pursue two main goals, one quite general and one relatively specific. The more general goal is to describe a theory of cognitive change – the overlapping waves approach – that has arisen from my own and other investigators' microgenetic studies. The more specific goal is to illustrate a use to which the microgenetic method is just beginning to be put, but one that it can serve very effectively: Helping us understand how instructional approaches exercise their effects. The particular instructional approach used to illustrate this function is encouragement to generate self-explanations, that is, encouragement to explain how or why events occurred. I first describe the general theory, then the specific application.

Overlapping waves theory

Implicit metaphors shape our thinking about many topics. A common implicit metaphor underlying traditional views of cognitive development was made explicit by the title of Robbie Case's (1992) book The mind's staircase. As shown in figure 1.1, the staircase metaphor suggests that children think in a given way for an extended period of time (a tread on the staircase); then their thinking undergoes a sudden upward shift.

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(a riser on the staircase); then they think in a different, "higher" way for another extended period (the next tread); and so on.

Although this depiction of development is most closely associated with the Piagetian and neo-Piagetian traditions, it also underlies many other approaches to development. For example, theory-theory approaches rest on a similar metaphor. Two-year-olds are said to have a desire theory of mind, whereas three-year-olds are said to have a belief-desire theory of mind; five-year-olds are said to have a psychological theory of biology until around age ten when they generate a truly biological theory; and so on (Carey, 1985; Wellman & Gelman, 1998). Information processing descriptions also often reflect the staircase metaphor. Thus, five-year-olds are said to solve simple addition problems by counting from one, seven-year-olds by counting from the larger addend, and nine-year-olds by retrieving the answer from memory (Ashcraft, 1987).

Most staircase depictions have been based on data aggregated across many children and many trials. They describe the main trend in the data. Microgenetic analyses, in which strategy use is assessed on a trial-by-trial basis, have allowed finer-grained examination of the change process. The results yielded by such trial-by-trial assessments of changing competence have been both consistent and surprising. Regardless of whether the tasks have involved problem solving, reasoning, language, memory, attention, or motor activity, and regardless of whether the children have been infants, toddlers, preschoolers, elementary schoolers, or adolescents, children use a variety of strategies (Adolph, 1997; Alibali & Goldin-Meadow, 1993; Coyle & Bjorklund, 1997; Granott, 1998; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; Miller & Aloise-Young, 1996; Schauble, 1996; Thelen & Ulrich, 1991; Thornton, 1999). Older, less advanced strategies
continue to be used long after newer, more advanced strategies have been discovered.

The variability also is present at every level of analysis, as can be seen through microgenetic studies of strategic development. It is present at the level of individuals as well as groups. Individual children have been found to use at least three strategies in such varied domains as arithmetic, spelling, scientific experimentation, and recall of previously presented information (Siegler, 1996). Variable strategy use also exists within a child solving a single problem on two occasions, close in time. Presented with a single addition problem, or a single analog clock time on two successive days, roughly one-third of children used a different strategy on the second day from the first (Siegler & McGilly, 1989; Siegler & Shrager, 1984). Variable strategy use is even evident within a single trial. A single presentation of a problem can elicit one strategy in speech and a different one in gesture (Alibali & Goldin-Meadow, 1993).

The fact that children use a variety of strategies over prolonged periods of time does not mean that strategy choices are random or that strategic development is directionless. Even infants and toddlers choose quite adaptively among strategies (Adolph, 1997; Chen & Siegler, 2000). For example, from the beginning of their experience with ramps, toddlers adjust their descent strategies to the steepness of the ramp. They use quicker but riskier strategies on the shallower ramps and slower but surer strategies on the steeper ones. With age and experience, their and older children's strategy choices become even more adaptive. Thus, toddlers' descent strategies become increasingly finely calibrated to the ramp's angle (Adolph, 1997).

Such findings indicate that the overlapping waves depiction, shown in figure 1.2, may be a more useful way of thinking about strategic development than the staircase metaphor. Within the overlapping waves depiction, children typically know and use a variety of strategies at any one time. With age and experience, the relative frequency of each strategy changes, with some strategies becoming less frequent (Strategy 1), some becoming more frequent (Strategy 5), some becoming more frequent and then less frequent (Strategy 2), and some never becoming very frequent (Strategy 3). In addition to changes in relative frequencies of existing strategies, new strategies are discovered (Strategies 3 and 5), and some older strategies cease to be used (Strategy 1).

At times, all or almost all of these changing patterns of strategy use are evident within a single study. Consider a study of number conservation (Siegler, 1995) in which five-year-olds were given a pretest and four training sessions. During the training sessions, children needed to
explain the logic underlying the experimenter's answer on each trial. As shown in figure 1.3, over the course of the experiment, reliance on the relative lengths of the two rows of objects decreased, reliance on the type of transformation that had been performed increased, reliance on counting and on the observation that the experimenter just moved the objects back and forth stayed at a constant low level throughout the experiment, and answering "I don't know" first increased and then decreased.

These descriptions of strategic change fit adults as well as children. Adults also use multiple strategies over prolonged periods of time; they continue to use earlier-formulated strategies, even after superior alternatives are available; and they choose adaptively among the strategies. Such findings have emerged in individual problem solving (Perry & Elder, 1999), collaborative problem solving (Granott, 1993), single-digit arithmetic (LeFevre, Bisanz, & Sadesky, 1996), spatial reasoning (Marquer & Pereira, 1990), and other domains. Also, as with children, adults' new strategies often involve recombination of subprocedures from previous ones (Anzai & Simon, 1979).

Thus, as Granott (1998) has emphasized, findings from microgenetic studies suggest that the traditional distinction between learning and development is, at minimum, overstated. Both children's learning and adults' learning in such studies display characteristics that are supposed to be on the developmental side of the dichotomy: Knowledge moves consistently from less to more advanced, rather than oscillating aimlessly; knowledge often is reorganized, rather than shifting in superficial ways; and learning is generative, in the sense that early advances form the foundation
for later ones. The findings that emerge from microgenetic studies also parallel those that arise from detailed cross-sectional studies of different age groups. Both types of studies reveal prolonged variability of strategy use, both within and between subjects, and increasingly adaptive choices among strategies as subjects gain experience in the domain. Thus, despite differences in the time spans of the changes, developmental and microgenetic change seem to be more similar than different.

The overlapping waves approach to strategic development has several advantages over staircase approaches. Most obviously, it fits the data better. Studies that have examined strategy use on a trial-by-trial basis have consistently revealed substantial variability. Older strategies continue to be used long after more advanced, newer strategies are also available. As illustrated in figure 1.3, this is true even when the tasks are ones that have been viewed as classic illustrations of staircase approaches, such as number conservation. Relying on the type of transformation yields consistently correct performance, relying on length does not, yet children continue to rely on length even after they are also relying on the type
of transformation. The overlapping waves approach also better captures the dynamic, continually changing character of development and focuses attention on discovery of new approaches as well as on choices among existing ones. Yet another advantage of microgenetic approaches is just beginning to be appreciated: It can help us understand how instructional approaches exercise their effects. The remainder of this chapter focuses on this application of microgenetic methods.

**Analyzing instructional manipulations**

Designing effective instructional procedures is a major challenge. Even after effective procedures have been designed, however, an equally large challenge remains: To understand how the procedures exercise their effects. Gaining such understanding is crucial to being able to improve the instructional techniques further and to utilizing them successfully in contexts other than the ones in which they were formulated.

Microgenetic methods have the potential to play a large role in addressing this problem. Examining the way that children learn under various instructional procedures, contrasting the characteristics of more and less successful learners, and identifying where learning goes awry when it goes awry – all can contribute to improving instructional procedures. Such analyses also can help us better understand learning and development. Once children enter school, much of the most important cognitive development occurs in the context of instruction. Understanding the types of instruction that benefit children of different ages, and understanding why older children often learn more effectively than younger ones, can deepen our theories regarding this crucial aspect of development.

A particular advantage of microgenetic studies for understanding how instruction exercises its effects lies in its ability to reveal the strategies that children develop in response to the instruction. Often, there are a variety of correct strategies for approaching a class of problems and a variety of incorrect strategies as well. Both classes of strategies vary in the range of problems to which they can be applied, in their ease of execution, and in the conceptual underpinnings needed to understand their functioning. As will be seen, children who are presented with the same instructional procedure often construct quite different strategies. Microgenetic studies can help us understand how and why this occurs.

The particular instructional approach that my colleagues and I have examined through microgenetic studies is encouragement to generate self-explanations. We next examine why encouraging children to generate such explanations is a potentially valuable instructional approach, and what is known about its effectiveness.
Background on self-explanations

Self-explanations are inferences about causal connections among objects and events. The inferences can concern how procedures cause their effects, how structural aspects of a system influence its functioning, how people's reasoning leads to their conclusions, how characters' motivations within a story lead to their behavior, and so on. In short, they are inferences concerning "how" and "why" events happen.

Ability to infer such causal connections is present from very early in life. Infants in their first year sometimes infer connections between physical causes and their effects (Leslie, 1982; Oakes & Cohen, 1995). Infants and toddlers also remember events that reflect a coherent causal sequence better than ones in which the causality is unclear (Bauer & Mandler, 1989). Thus, ability to explain the causes of events seems to be a basic property of human beings and influences many aspects of cognition including memory, problem solving, and conceptual understanding.

Although very young children can generate causal connections, even older children and adults often fail to do so. This poses a particular problem in math and science instruction. Math and science teachers frequently lament the fact that their students can execute procedures but have no idea why the procedures work. Such situations reflect failures of self-explanation. The problem can be illustrated in the context of buggy subtraction (van Lehn, 1983). On problems requiring subtraction across a zero, such as 704 - 337, second- through fifth-graders (seven- to eleven-year-olds) generate a variety of incorrect answers. These answers usually reflect misunderstandings of how the procedure works, rather than carelessness. For example children often subtract across a zero without decrementing the number from which the borrowing was done. On 704 - 337, this would produce the answer 477. Such procedures reflect children knowing the superficial form of the long subtraction algorithm but not understanding why it generates the answers that it does.

Another type of evidence for the importance of self-explanations comes from studies of individual differences in learning. One difference between better and worse learners is the degree to which they try to explain what they are learning. In a wide range of areas, including physics, biology, algebra, and computer programming, frequency of explaining the logic underlying statements in textbooks is positively related to learning the material covered in the textbook (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994; Ferguson-Hessler & de Jong, 1990; Nathan, Mertz, & Ryan, 1994; Pirolli & Recker, 1994). The kinds of explanations that seem most effective involve constructing causal connections between procedures and their effects, as well as between
structural, functional, and behavioral aspects of systems and sub-systems (Chi, 2000).

The positive relation between learning and generation of self-explanations is not entirely attributable to people of higher ability generating a greater number of explanations than those of lower ability. Both high and low scorers on standardized achievement tests who generate a greater number of such explanations learn more than those who do not (Chi et al., 1994). Nor is it attributable to those who generate a greater number of explanations spending more time on the task. Generating explanations does take time, but equating the time spent on the task by having a control group read the textbook material twice did not result in as much learning as generating the explanations on a single reading (Chi et al., 1994).

Another type of evidence for the positive effects of self-explanations on learning comes from studies of math teaching practices in Japan (Stigler & Hiebert, 1999). Levels of math learning in Japan are at consistently high levels. For example, in one comparison of fifth-graders, the mean level of math achievement in all ten Minneapolis schools that were examined was below the mean level of any of the schools examined in a comparable community in Japan (Stevenson, Lee, Chen, Stigler, Hsu, & Kitamura, 1990). One contributing factor to these differences seems to be differing degrees of emphasis on generating explanations for why mathematical algorithms work. In Japanese classrooms, both teachers and students spend considerable time trying to explain why solution procedures that differ superficially generate the same answer, and why seemingly plausible approaches yield incorrect answers. Encouraging children to explain why the procedures work appears to promote deeper understanding of them than simply describing the procedures, providing examples of how they work, and encouraging students to practice them – the typical approach to mathematics instruction in the US (Stigler & Hiebert, 1999).

Thus, when my colleagues and I began the present series of investigations, we knew that amount of self-explanation and amount of learning were correlated. We did not know, however, whether there was a causal relation between the two. It might be the case, for example, that more intelligent and more highly motivated children might learn more and generate more explanations, but the self-explanatory activity might not cause the greater learning. Only by randomly assigning children to conditions under which they were or were not encouraged to engage in explanatory activity could causal linkages between the two be drawn.

The particular form of self-explanation instruction that we have examined involves asking children to explain the reasoning of another person. In particular, children are presented with a problem, they advance
an answer, they are given feedback concerning the correct answer, and then the experimenter asks them, "How do you think I knew that?" This instructional procedure was of particular interest because it can be used on virtually any task, it is easy to execute, and it can be used with a wide range of age groups.

The detailed data about learning that is yielded by microgenetic methods provides a means for finding out not only whether such encouragement enhanced learning but also why it did or did not work for individual children. The investigations have been aimed at answering six main questions:

1) Is self-explanation causally related to learning as well as being correlated with it?
2) Do young children, as well as older individuals, benefit from encouragement to provide explanations?
3) Is explaining other people's reasoning more useful than explaining your own reasoning?
4) What individual difference variables influence ability to benefit from self-explanations?
5) Is explaining both correct and incorrect reasoning more useful than just explaining correct reasoning?
6) How does encouragement to explain generate its effects?

The remainder of this chapter reports our efforts to answer these six questions. More generally, it illustrates how microgenetic studies can help reveal the workings of instructional approaches.

**Explaining number conservation**

The first context in which we examined the causal influence of self-explanations involved five-year-olds performing number conservation problems (Siegel, 1995). The task closely resembled the classic Piagetian procedure. Children were shown two parallel rows, each with the same number of objects (seven, eight, or nine, depending on the item), arranged in 1:1 correspondence. At the beginning of each trial, children readily agreed that the two rows had the same number of objects. Then, one of the rows was transformed spatially (by lengthening the row; shortening it, or leaving the length unchanged) and quantitatively (by adding an object, subtracting an object, or doing neither). The experimenter called attention to both spatial and numerical transformations, by saying (for example) "Now I'm spreading this row out and I'm taking an object away from it." Children in all groups were then asked whether
they thought the transformed row had more objects, fewer objects, or the same number of objects as the untransformed row.

Children in all groups were first given a pretest. Those whose performance indicated that they did not yet know how to solve number conservation problems then spent four sessions participating in one of three training procedures. One group of children received feedback alone; they advanced their answer and were immediately told whether it was correct or incorrect (feedback-only condition). A second group of children advanced their answers, were asked, "Why do you think that?" and then were given feedback on their answer, as in the feedback-only condition (explain-own-reasoning condition). In collaborative learning experiments, the children who learn the most tend to be those who advance elaborate explanations of their own reasoning to other children (King, 1991; Webb, 1989). Examining this condition allowed us to determine whether describing one's own reasoning was causally related to learning.

A third group of children advanced their answers, received feedback from the experimenter concerning which answer was correct and then were asked by the experimenter "How do you think I knew that?" (explain-correct-reasoning condition). This last condition, in which the child needed to explain the experimenter's reasoning, was of greatest interest. Having children explain another person's correct reasoning combines advantages of discovery and didactic approaches to instruction. It is like discovery-oriented approaches in that it requires the child to generate a relatively deep analysis of a phenomenon without being told how to do so. It is like didactic approaches in that it focuses the child's attention on correct reasoning. Thus, it combines some of the efficiency of didactic instruction with some of the motivating properties of discovery.

Trying such instruction with young children was of particular interest. Although young children can and do try to explain other people's reasoning, their frequent egocentrism and lack of reflection seem to lead them to do so less often than older individuals. If this is the case, then instructions to try to explain to oneself the reasoning of a more knowledgeable individual may be especially useful for young children.

The results indicated that, as hypothesized, encouraging children to explain the reasoning underlying the experimenter's answer resulted in their learning more than feedback alone or feedback in combination with requests to explain their own reasoning (figure 1.4). The differential gains were largest on the most difficult problems, those in which relying on the length cue led to the wrong answer.

These findings, though interesting, could have been obtained in a conventional training study. Other results from the study, however, could not have been obtained without the trial-by-trial analysis of change made
possible by microgenetic methods. The advantages of the microgenetic data were especially evident in analyzing performance and learning of children in the explain-correct-reasoning group, the group that showed the greatest learning.

One such finding was that even in a logical domain such as number conservation, a variety of ways of thinking coexisted both before and while the instruction was presented. As shown in figure 1.3, children explained the experimenter's reasoning in five qualitatively distinct ways: the type of numerical transformation, the relative lengths of the rows, counting the objects in each row and choosing the row with the greater number, saying the objects were just moved back and forth, and saying that they didn't know why the experimenter had answered as she had.

Variability of reasoning was evident in all phases of the experiment. On the pretest, only 7% of children relied on a single strategy on all trials. Of the other children, 20% used two approaches, 47% used three approaches, and 27% used four approaches. Thus, the large majority of children used three or more strategies on the pretest.
A surprising aspect of the pretest results was the fact that most children explicitly cited the type of transformation at least once. The overall percentage of citations of the type of transformation was low – 9%. The low percentage was logically necessary, because children who used transformational explanations on more than 25% of pretest trials were excluded from further participation in the experiment. Despite this restriction, most children showed some knowledge of the influence of the type of transformation on the number of objects. Thus, even before the training session began, the sophisticated transformational explanation coexisted with less sophisticated strategies, such as those based on length and counting.

This diversity of strategy use continued during the four training sessions. In each of these sessions, only about 10% of children relied on a single strategy.

The microgenetic design also made possible detailed analysis of the way in which the request to explain the experimenter’s reasoning produced its effects. As shown in figure 1.3, the pattern of change clearly was more akin to that envisioned in the overlapping waves model than in the stair-step model. On the pretest, the children explained most of their answers by saying that the row they chose was longer (or by saying that the two rows had the same number of objects because the rows were equally long). When they initially needed to explain the experimenter’s reasoning, in the first training session, most children could not generate a good explanation; their most frequent response was that they didn’t know why the experimenter had answered as she had. This explanation was used more than twice as often as explanations in which they cited the type of transformation. However, by the second training session, they were citing the type of transformation just as often as saying that they did not know, and in the third and fourth training sessions, their most frequent explanation was to say that the experimenter had based her judgment on the type of transformation. Thus, the group-level data suggested that the major source of change was children de-emphasizing length and emphasizing the type of transformation that was performed.

The dense sampling of changing performance yielded by the microgenetic analysis allowed examination of individual children’s change patterns as well as those of the group as a whole. The analyses of individual children indicated that the group-level change pattern corresponded to the single most common pattern of change at the individual level, but that two other patterns of change also occurred. In particular, identifying for each child the type of explanation that underwent the largest increase from the pretest to the last training session and the type of explanation that underwent the largest decrease over the same period indicated three
distinct patterns of change: large increases in reliance on transformations and large decreases in reliance on length (53% of children), large increases in saying "I don't know" and large decreases in reliance on length (27%), and idiosyncratic change patterns (20%).

These changes in explanations proved highly predictive of changes in percentage of correct answers. Children in the decreased-length/increased-transformation sub-group progressed from 49% correct on the pretest to 86% correct in the final session of the training period. Children in the other two sub-groups did not increase their accuracy at all over the same period; they answered correctly 52% of pretest items and 50% of items in the last training session. This result left little question that the source of learning from explaining the experimenter's reasoning came from recognizing the rule of the type of numerical transformation in her reasoning. Those children who came to explain the experimenter's reasoning in terms of transformations substantially increased the accuracy of their own judgments. Those children who did not showed little or no improvement in the accuracy of their own judgments.

How did the children who benefited from the requests to explain the experimenter's reasoning differ from those who did not benefit? To answer this question, a regression analysis was conducted in which several characteristics of children and their pretest performance were used to predict amount of learning (defined as percent correct answers over the four training sessions). Three predictors accounted for 65% of the variance in learning: number of different explanations that the child used on the pretest (right or wrong), whether the child ever advanced two explanations on a single pretest trial, and the child's age. The first two predictors—number of different explanations and use of multiple explanations on a single trial—both indicated that the children who learned the most were the children whose pretest performance was the most variable.

Thus, variability of children's thinking prior to training was positively related to learning. This finding is consistent with results in which rats, pigeons, and adult humans have been presented with experimental procedures that increased their behavioral variability (Baer, 1993; Neuringer, 1993; Stokes, Mechner, & Balsam, 1997). It also is consistent with results from microgenetic studies in which children's understanding is assessed on each trial via both gesture and speech. Children whose gestures and speech on a pretest frequently reflect divergent reasoning are more likely to learn (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986). Verbal inarticulateness, as reflected in false starts and long pauses, also is positively related to learning (Perry & Lewis, 1999).

The positive relation between initial variability and later learning makes sense; use of more varied approaches increases opportunities to explore
the task environment and to discover hitherto unexpected aspects of it. Relatively great initial variability also may be indicative of an openness to new approaches. In addition, part of the effectiveness of many forms of instruction may lie in their leading children to try more varied approaches. In the Siegler (1995) study, for example, children who were asked to explain the experimenter's reasoning advanced more different types of explanations than did peers asked to explain their own reasoning. Thus, part of the reason for the effectiveness of requests to explain the experimenter's reasoning may have been that it encouraged generation of varied possibilities, some of which were more effective than the approaches that children usually used.

The findings from the Siegler (1995) study of number conservation provided answers to four of the six questions about self-explanation posed earlier in this chapter. With regard to the first question, encouraging children to explain other people's reasoning is causally related to learning. Children who were randomly assigned to explain the experimenter's reasoning learned more than children who explained their own reasoning. Studies conducted in other laboratories have shown that the people whose reasoning is being explained need not be present for the positive effects to emerge. Encouraging children and adults to explain the reasoning that they encounter in textbooks has similar benefits (Chi et al., 1994; Bielaczyc, Pirolli, & Brown, 1995).

The results also indicated positive answers to the second and third questions. Children as young as five years, as well as older children and adults, benefited from being asked to explain other people's reasoning, and explaining other people's correct reasoning was more beneficial than explaining the mix of correct and incorrect reasoning that children themselves generated. With regard to the fourth question, individual differences in learning were positively related to variability of initial reasoning. Additional experiments were necessary, however, to address the fifth and sixth questions.

**Explaining mathematical equality**

Within recent computer simulation models of strategy choice, such as ASCM and SCADS (Shrager & Siegler, 1998; Siegler & Shipley, 1995), the likelihood of a strategy being used on a problem is a positive function of its own effectiveness and a negative function of the effectiveness of competing approaches. For example, although children can solve \(2 + 2\) very quickly and accurately by counting from 1, they rarely use that approach, because they can solve \(2 + 2\) even more quickly, and just as accurately, by retrieving the answer from memory. Similarly, a strategy that is not particularly fast and accurate will be used often if alternative approaches
are even less effective. Thus, the likelihood of using a given strategy can be increased in two ways: increasing its own strength or decreasing the strength of alternative strategies.

This issue arises frequently in instructional contexts in which less-advanced previous approaches continue to be used after more advanced new approaches are also employed. The computer simulations suggest that the best way to increase the use of the new, more advanced approaches should be to increase their strength and also to decrease the strength of less advanced approaches. In the context of self-explanation, having children explain both why correct approaches are correct and why incorrect approaches are incorrect should be more effective than only explaining why correct approaches are correct. Explaining how correct answers were generated and why they are correct should increase the strength of correct procedures, and explaining how incorrect answers were generated and why they are wrong should decrease the strength of incorrect procedures.

I tested this prediction on a task developed by Perry, Church, & Goldin-Meadow (1988). This task involves problems of the form A + B + C = ___ + C. Third- and fourth-graders find such problems surprisingly difficult. For example, they usually answer 3 + 4 + 5 = ___ + 5 by writing “12.” This answer reflects an add-to-equal-sign strategy, in which the children add all numbers to the left of the equal sign. The next most common answer to the problem is 17, which reflects an add-all-numbers strategy (see Goldin-Meadow & Alibali, this volume). Both approaches reflect limited understanding of what the equal sign means. The third and fourth graders seem to interpret it as a signal to add the relevant numbers, rather than as an indication that the values on the two sides of the equal sign need to be equivalent.

In the experiment that I ran on this task (Siegler, in preparation), eighty-seven third- and fourth-graders were presented with a procedure that included three phases: pretest, training, and posttest. The pretest and posttest included three types of problems: A + B + C = ___ + C (C problems), A + B + C = ___ + B (B problems), and A + B + C = ___ + D (D problems). These problems differed in the relation of the number after the equal sign to the numbers before it. On “C problems,” the number after the equal sign was identical to the rightmost number before it (e.g., 3 + 4 + 5 = ___ + 5). On “B problems,” the number after the equal sign was identical to the middle number before it (e.g., 3 + 4 + 5 = ___ + 4). On “D problems,” the number after the equal sign did not match any of the numbers before it (e.g., 3 + 4 + 5 = ___ + 6).

The reason for including these three kinds of problems was that they were solvable by different types of strategies. One strategy worked only on C problems: just add the first two numbers. A second strategy worked
on both B and C problems, but not on D problems: locate a number that is present on both sides of the equal sign, and add the other two numbers. Two other strategies worked on all types of problems. One of these optimal strategies was to create equal values on the two sides of the equal sign (e.g., on $3 + 4 + 5 = \_ + 5$, add the numbers on the left and solve $12 = \_ + 5$). The other optimal strategy was to subtract from both sides the number on the right side of the equation (e.g., on $3 + 4 + 5 = \_ + 5$, subtract 5 from both sides and solve $3 + 4 = \_$. Thus, presenting these three types of problems allowed assessment of children's strategy use before and after training.

The training procedure included ten problems. The ones of greatest interest were the six C problems, such as $3 + 4 + 5 = \_ + 5$. The other four items were standard three-term addition problems with no numbers on the right side of the equal sign, such as $5 + 6 + 7 = \_$. These four problems were included to prevent children from reflexively adding the first two numbers on all problems. Performance on these foils was virtually perfect in all conditions and will not be described further.

Children received the ten problems under one of three training conditions. Children in the explain-own-reasoning condition were asked to answer a problem, then asked to explain why they thought their answer was correct, and then given feedback about the answer (either “You’re right, the answer is N” or “Actually, the correct answer is N”). Children in the explain-correct-reasoning condition were first presented with a problem, asked to answer it, and given feedback as to the correct answer. They then were told that a child at another school had answered N (the right answer), asked how they thought the child had done so, and asked why they thought that was the right answer. Finally, children in the explain-correct-and-incorrect-reasoning condition were presented with the same procedure, except they were asked to explain not only the reasoning of a hypothetical child who had generated the right answer but also the reasoning of a hypothetical child who had generated a wrong answer. The wrong answer that children in this condition needed to explain matched the answer that would have been generated by the procedure that that child had used most often on the pretest.

Pretest performance of this sample closely resembled that described in previous studies in which this task was used. Children usually employed the add-to-equal-sign strategy. A minority of children used the add-all-numbers approach. Percent correct was 0% for children in all three conditions, and mean solution time was around 10 s in all conditions and did not differ among them. (These figures exclude the performance of nine children who answered most pretest items correctly and therefore did not participate further in the study.)
As shown in figure 1.5, children in all conditions learned a considerable amount during training. However, those who were asked to explain both why correct reasoning was correct and why incorrect reasoning was incorrect learned more than those in the other two groups. The differences were maintained on the posttest. Children who were asked to explain both correct and incorrect reasoning improved from 0% correct on the pretest to about 70% correct during training and on the posttest. Children in the other two groups progressed from 0% correct answers on the pretest to about 50% correct during training and on the posttest. The absolute level of learning of children who were asked to explain the correct answer was quite high, but so was that of children who were given feedback and asked to explain their own answer.

As shown in figure 1.6, the superior posttest performance of children who explained both correct and incorrect answers during training was due largely to their being better able to solve the problems that required relatively deep understanding (B and D problems). Analysis of changes in explanations during the training phase made clear the source of this
effect. Children in all groups greatly decreased their use of the add-to-equal-sign strategy that had predominated on the pretest. The decrease occurred more quickly in the group in which children needed to explain why that strategy was wrong (figure 1.7), but over the six trials it occurred in all three groups to large extents. However, the groups differed considerably in the new strategies that children adopted. Children who only explained their own reasoning largely adopted the simplest strategy, that of adding A + B (figure 1.8). In contrast, children who explained both why correct answers were correct and why incorrect ones were incorrect were more likely to use the advanced strategies of equalizing the two sides or eliminating the constant on the right side of the equal sign by subtracting its value from both sides (figure 1.9).

The strategies that children adopted to explain correct answers during the training period proved to be very predictive of their own posttest performance. Frequency of adopting one of the two advanced strategies
correlated \( r = 0.77 \) with percent correct on the B problems on the posttest and \( r = 0.86 \) with percent correct on the D problems on the posttest. In contrast, percent use of the A + B explanations during training correlated \( r = -0.70 \) with percent correct on the B problems on the posttest and \( r = -0.76 \) with percent correct on the D problems. Thus, asking children to explain why correct answers were correct and why incorrect answers were incorrect led to deeper understanding of the problems, as indicated by adoption of strategies that would solve a broader range of problems rather than just the problems in the initial training set.

Changes in solution times over the six trials of the training period shed additional light on the change process for children in the three groups. As shown in figure 1.10, on Trial 1, times for children in all three groups were around 12 s. The lack of difference made sense, because children in all groups had been treated identically up to this point. However, for those children who were asked to explain either correct reasoning or correct and
incorrect reasoning at the end of Trial 1, solution times approximately doubled on Trial 2. On Trial 3, solution times of children who were asked to explain both correct and incorrect reasoning started to decline and the times continued to decline thereafter. In contrast, mean solution times of children who were asked to explain only correct answers increased to 26 s on Trial 3, before decreasing substantially over the remaining trials.

Why did the solution times of children asked to explain another child’s reasoning show these changes? Consideration of data on each child’s trial of last error during the training phase suggested a simple explanation. Most children who were asked to explain both correct and incorrect reasoning made their last error on Trial 2. The next most common outcome was for their last error to occur on Trial 3. Thus, their solution times for explaining the correct reasoning increased from Trial 1 to 2, when they became confused about how the correct answer was generated, and
the times decreased thereafter as the children increasingly understood how to generate the correct answer. In contrast, most children who were asked only to explain the correct answer did not make their last error until Trial 3, and a number of them made their last error on Trial 4. This suggested that one or more incorrect procedures continued to compete with the correct procedure for a longer time, resulting in their solution time on Trial 3 being much greater than that of children who explained both correct and incorrect answers.

Thus, requests to explain correct answers, or correct and incorrect answers, led to an initial period of cognitive ferment, characterized by incorrect answers and very long solution times. Then children induced one or more strategies for solving the problems, and thus for explaining correct answers. This led to their consistently answering correctly and to their solution times becoming much shorter. Children who were asked
to explain both correct and incorrect answers tended to cease relying on their previous incorrect approach more quickly than did children who only were asked to explain correct answers, and they tended to settle on more widely applicable new strategies as well.

These findings are reminiscent of previous ones indicating that just prior to discoveries, children show increased solution times (Siegler & Jenkins, 1989), increased verbal disfluencies (Perry & Lewis, 1999), increased gesture-speech mismatches (Alibali & Goldin-Meadow, 1993), and increased cognitive conflict (Piaget, 1952). They also are reminiscent of the previously described number conservation findings from Siegler (1995), in which pretest variability was positively related to subsequent learning. In all cases, learning seems to involve children moving from incorrect approaches to a state of high uncertainty and variability, and then to a period in which the uncertainty and variability gradually decrease as children increasingly rely on more advanced approaches. The process occurs much faster in situations such as number conservation and mathematical equality, in which the less advanced approaches generate wrong.
answers, than in situations such as addition and time telling, in which the less advanced approaches generate correct answers but do so relatively inefficiently.

Thus, the answer to Question 5 seems to be: Children do learn more from being asked to explain both why correct answers are correct and why incorrect answers are incorrect than from being asked only why correct answers are correct. Findings from a very recent study of the water displacement task (Siegler & Chen, in preparation) yielded converging findings. There too, children learned more from being asked to explain both correct and incorrect answers than from being asked only to explain correct answers. This leaves the last, and most challenging, of the six questions, for final consideration.

How does self-explanation help children learn?

Self-explanation seems likely to generate its effects through several distinct mechanisms. Data from the present studies of number conservation and mathematical equality provide evidence for at least four of them.

One way in which encouragement to explain exercises its effects is to increase the probability of the learner seeking an explanation at all. When people are told that an answer is wrong, they often simply accept the fact without thinking about why it is wrong or how they might generate correct answers in the future. The number conservation data provide evidence regarding this source of effectiveness. Children who were told that their answer was wrong and which answer was right, but who were not asked to explain why the correct answer was correct, did not increase the accuracy of their answers over the course of the four sessions. In contrast, children who received the same feedback but who also were asked to explain how the experimenter had generated the correct answer, did increase their accuracy. Further, those children who showed the largest increases in successfully explaining the experimenter's reasoning also showed the largest increases in generating correct answers on their own. Thus, encouragement to generate self-explanation seems to work partially through encouraging children to try to explain observed outcomes.

Even when children try to explain what they have seen or been told, they vary in the depth of their search for an explanation. A second way in which encouragement to explain exercises its effects is through increasing the depth of explanatory efforts. The study of the mathematical equality task provides relevant evidence. Children in all three groups succeeded in finding ways to solve the problems by the second half of the training period. However, children who were asked to explain correct and
incorrect answers appeared to search considerably more deeply. They more often generated conceptually more sophisticated solutions, such as balancing the values on the two sides of the equal sign. In contrast, children who were only given feedback usually generated solutions to the training problems that happened to work on those problems but were not generally applicable (the A + B strategy). Thus, encouraging generation of explanations also seems to promote a deeper search than might be undertaken otherwise.

It should be noted that both of these mechanisms also have the effect of increasing the variability of the procedures that children attempt. For example, in the number conservation study, children who were asked to explain the experimenter’s answer generated a greater number of strategies than did children who were only given feedback concerning their own answers. This difference was present despite feedback per se often increasing variability of responses (Neuringer, 1993). Thus, increasing the likelihood of searching for an explanation and the depth of the search if one is undertaken seem to operate in part by increasing the range of strategies that children attempt.

A third likely mechanism involves changing the accessibility of effective and ineffective ways of thinking. The most directly relevant evidence here comes from the mathematical equality study. Children who were asked to explain why incorrect answers were incorrect as well as why correct answers were correct showed more rapid decreases in use of their previous A + B + C strategy than did children who were only asked to explain why correct answers were correct. This was what models such as ASCM and SCADS would predict. Instructional approaches that not only strengthen effective approaches but that also weaken ineffective ones should increase the likelihood of retrieving the effective approaches and decrease the likelihood of retrieving ineffective ones.

A fourth set of mechanisms involves more general processes related to degree of engagement with the task. One concerns motivational effects. Learning is more enjoyable when what you are learning makes sense. By encouraging children to make sense of their observations, encouragement to generate explanations achieves this motivating effect. A second, related benefit involves depth of processing; encouraging children to explain what they see or are told leads them to process the information more deeply than they otherwise might. A third general benefit involves increased time spent actively engaged in thinking about the problem. The more time that children spend trying to understand why correct answers are correct and why incorrect answers are incorrect, the more they are likely to learn.
Thus, the two microgenetic studies yielded answers to all six questions posed earlier in the chapter. They demonstrated:

1) Encouragement to explain other people's statements is causally related to learning;
2) Five-year-olds as well as older children can benefit from encouragement to explain;
3) Explaining other people's answers is more useful than explaining your own, at least when the other people's answers are consistently correct and your own answers include incorrect ones;
4) Variability of initial reasoning is positively related to learning;
5) Explaining why correct answers are correct and why incorrect answers are incorrect yields greater learning than only explaining why correct answers are correct;
6) The mechanisms through which explaining other people's reasoning exercises its effects include increasing the probability of trying to explain observed phenomena; searching more deeply for explanations when such efforts are made; increasing the accessibility of effective strategies relative to ineffective ones; and increasing the degree of engagement with the task.

Thus, microgenetic studies are useful for both general and specific purposes. At a general level, they have provided much of the underpinning of the overlapping waves model, a broad framework for thinking about development. At a more specific level, they have proved useful for understanding how instructional procedures, such as encouragement to explain other people's reasoning, exercise their effects. As amply documented in other chapters in this volume, they have many additional uses as well.

References


