

Cognitive Development and Education:
From Dynamic General Structure to Specific Learning and Teaching

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Note. We dedicate this chapter to the memory of our friend and colleague, Robbie Case, who died too young in the midst of a good, strong, productive life as a premier cognitive educational scientist. Preparation of this chapter was supported by the Spencer Foundation, and some of the work reported was supported by grants from Mr. and Mrs. Frederick P. Rose, Harvard University, NICHD (grant #HD32371), a Spencer Research Training Grant to Harvard University, and the Harvard Graduate School of Education. The authors thank Catherine Ayoub, Thomas Bidell, Daniel Bullock, Robbie Case, Nira Granott, Jane Haltiwanger, Catherine Knight, Pamela Raya, Samuel Rose, Robert Thatcher, Paul van Geert, Malcolm Watson, John Willett, and Zheng Yan for their contributions to development of our arguments and evidence.

Executive Summary

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Discoveries from cognitive science have overthrown dominant assumptions about learning and development and led to new knowledge and methods that create a strong framework to ground educational research and practice.

1. Cognitive science failed in its broadest goal – the discovery of universal mental structures based in logic, as hypothesized by Piaget, Chomsky, and others. At the same time cognitive research established that people construct knowledge through their activity, and that development and learning show remarkable variability across people, tasks, and cultures. That variability turns out to be an asset in understanding learning and development.

2. What is universal is not a mental structure but the processes of cognitive development and the scale for such growth. In a common process, people construct skills by first using two or more distinct, often contradictory skills that co-occur for the same situation. This process is usually social, with several people building skills together. They explore the co-occurring skills in order to create a new skill, which they apply readily within a content domain but not across domains. As a result, development moves along parallel, independent strands (domains) in a developmental web. The strands are independent, yet they grow through similar processes and follow a universal scale of predictable developmental levels.

3. Short-term learning and long-term development involve the same processes, a relation that greatly increases the usefulness of cognitive developmental science to education. Analysis of these processes begins with the variability of knowledge and activity, not only between people but within a person or collaborating group from moment to moment. In the short term, people frequently move to low skill levels to learn something new, and repeatedly build and rebuild their skills until they create a relatively stable understanding or activity. In the long term, the upper limit on skill develops in a series of fits and starts marking the emergence

of new capacities. This upper limit occurs primarily with high contextual support, when experts or artifacts (text, diagrams, tools) provide immediate support for complex performance.

4. The search for middle-level, domain-specific general structures has mostly failed (perspective-taking, metamemory, metacognition, theory of mind, etc.), with little evidence of generalization across tasks and contexts. Overall, generalization is difficult to attain in either laboratories or classrooms, apparently because it occurs only after long periods of repeated reconstruction. However, recently Case and his colleagues have succeeded in finding such a general structure, which they call the central conceptual structure for number. We hypothesize that this and other central conceptual structures achieve their generality through social support from specific linguistic and cultural practices that embody each structure.

5. This cluster of concepts and tools from cognitive science combine with the technological and mathematical tools of the twenty-first century to make possible a new cognitive science of education – one grounded in analysis of detailed data on learning in real-life settings such as schools. We can now study learning processes in classrooms and other settings and assess learning, teaching, and knowledge in context, instead of only through independent group tests. We can explicitly assess learning and development for each student or collaborating group. This new cognitive science of learning and development can radically alter the nature of educational research and provide powerful tools for improving educational practice through feedback of assessment results to classroom practices.

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Cognitive science in various guises has dominated the behavioral sciences for over a century. This influence has been highly productive, even though cognitive science has failed to achieve its broadest goal – the discovery of universal mental structures based in logic. The knowledge built from the search for universal structures has led to a new understanding of the mind and a powerful approach to cognition and learning, based in the intersection of nonlinear dynamics, structural analysis, ecological and cultural studies, and pragmatic philosophy. This approach takes the great variability of human activities as the starting point for explaining the commonalities of mind and development. It connects culture, biology, and individual growth within one framework. It promises to create tools for bringing together individual and group frameworks, analyzing individuals' learning and teaching in combination with cultural, family, and school practices.

Research in cognitive science – and particularly cognitive development – has focused primarily on the search for far-reaching, universal structures underlying knowledge and action, preferably structures grounded in logic or derived from it. Piaget and Chomsky established the frameworks for this search in cognitive development and language, respectively, and researchers and theorists have pursued it vigorously. If the search had been successful, it would have uncovered broad structures that would not only explain the nature of the mind, but also provide powerful educational tools for teaching broad, generalizable knowledge across domains.

Instead of uncovering broad, powerful mental and linguistic structures, the many tests of hypothesized general structures have found highly specific skills and abilities, tied to domain, task, culture, and experience. For example, despite Chomsky's (Chomsky, 1957, 1995) periodic assertion that "we all speak the same language," children who grow up learning Chinese cannot use that knowledge to understand English without great labor. Similarly for logic, students who learn symbolic logic cannot use it readily to write a good essay or analyze a chemistry

experiment.

At the same time, the search for general structures has uncovered (a) important, broad principles and processes for explaining the mind, including cognitive and language development and (b) useful methods and tools for analyzing learning and teaching. Many of the principles, processes, and tools from cognitive science apply across the multiple domains of the mind, even though they do not involve a single, coherent mental structure. *Development and learning occur along many parallel, independent strands that have similar properties even though they form separate cognitive structures.*

Learning and teaching are the core of education. Explaining the knowledge and methods from cognitive science that illuminate learning and teaching requires viewing development from three distinct perspectives. The *view from afar* examines the big picture of cognitive development – how the search for the broadest logical structures has led to important insights about cognitive growth across the months and years from infancy to early adulthood. The *middle view* considers analysis of intermediate changes – how the search for structures to explain cognitive change limited to one or another broad domain has failed repeatedly, and then finally succeeded when cultural, ecological contributions were added to the analysis. The *view up close* analyzes learning and problem-solving in the short term, searching for mechanisms of change to facilitate analysis and intervention across the diverse domains of intelligence.

The knowledge that arises from the successes of the view from afar and the middle view make possible a new kind of educational science: Short-term learning and long-term development combine in a single portrait of cognitive change, connected through the tools of nonlinear dynamics and growth modeling and combining insights and cautions gleaned from diverse viewpoints – Piagetian, information processing, learning theory, Vygotskian, and linguistic, among others. The new, integrated paradigm makes possible innovations in research on development, learning, and teaching that can greatly increase the usefulness of cognitive developmental science to education.

The View from Afar: The Big Picture of Cognitive Development

Historically, research on cognitive development has begun with the widely held assumption that mind and brain are organized around broad, domain-independent, universal structures. In research extending over most of the twentieth century, these structures have proven forever elusive, with a long series of hypotheses and empirical efforts failing again and again to demonstrate consistency in terms of a broad structure for the mind. These failures derive from the inherent inadequacy of such universal structures for explaining the natural variation, 'slippage,' jumps, and drops that mark real behavior and thought, real learning and problem solving. At the same time, the search for general structures has yielded important insights about the nature of cognitive development, especially through the creation of new methodologies and developmental scales.

Although the search has proved fruitless for broad logical structures underlying knowledge, language, and action, cumulating research evidence has provided a clear, useful portrait of the big picture of cognitive development: We start the twenty-first century with a clear depiction of how people learn and know and a strong framework for describing the common shapes of development and learning through childhood and adolescence. To better see how the emerging dynamic approach builds on the shoulders of the search for universals, we will first briefly examine the approaches that undergird it: Piagetian theory, information processing, learning theory, and neo-Piagetian structuralism, with its continued focus on logic, rationality, and competence. The approach that builds on the insights of these approaches and moves beyond their limitations is dynamic constructivism, which promises great advances for the science of education in the new millennium.

Piaget and the Universal Logic of the Mind

In the late 1960's and early 1970's, Piaget's (1968/1970; 1983) structuralism, with its search for the underlying logic of the mind, became the major influence in the study of cognitive development and education. Unlike the dominant behaviorist perspective of the time, Piaget moved beyond associative learning principles to understand the mind as actively constructing and interpreting the environment, in accordance with a set of logical and experience-dependent

universals. He described two complementary processes in particular, by which he proposed that people use their minds to *adapt* to their surroundings. *Assimilation* is the process of applying one's current understandings to happenings and interactions in the world, and *accommodation* is the process of adjusting one's thinking to better incorporate feedback from those objects and events. These two processes, he asserted, were mutually dependent and essential for the construction of knowledge, such that they always appear together and constrain and feed off one another. In moving between these complementary, broad-based, biological processes, each child builds a universal mental logic based on reversibility, enabling him or her to do and undo mental operations and to move back and forth through a set of elements, such as numbers or actions. In this way, cognitive development for Piaget was the process of building a set of cognitive structures or schemes based in the reversibility of actions. In this analysis he combined the insights of pragmatic philosophy with those of European structuralism, especially in logic, mathematics, and biology.¹

Piaget's framework, research agenda, and detailed, insightful observations of children's cognitive activities continue today to dominate most research and theory in cognitive development; but his focus on combining activity with structure has fared better than his particular emphasis on logic as the foundation of the mind. The collection of approaches that analyze activity structures is called "constructivism." Piaget expected logic to serve as the fundamental structure of the mind, with a succession of developing logics pervading the mind and thus creating a series of equilibrated stages of knowledge and understanding. Logic was the crux of the general structure of the mind, he hypothesized. Constructivist frameworks range from approaches that continue to search for universal logical structures in the mind to approaches that search for diverse structures based in action instead of universal structures.

As a gifted observer, Piaget (1937/1954) noted from his early work with his own infants that children showed *décalage*, or unevenness, in skills. For example, his children developed

¹ Important influences on Piaget's theory included the following: For pragmatic philosophy C.S. Peirce, W. James, E. Durkheim, J. M. Baldwin, and F. de Saussure ; for logic and mathematics, E. Cassirer, É. Galois, H. Poincaré, F. Klein, and the Bourbaki group; for biology C. Darwin, C. Waddington, and L. von Bertalanffy

person permanence before object permanence late in the first year of life. Documenting these inconsistencies in the ways that logical action and thought played out in the development of real children became an obsession among English-language researchers. Children do not show the clean, stage-like progressions in their reasoning that Piaget expected. No given child acts consistently at a particular stage across domains, and a child's logical insights in one domain do not automatically carry over to other sorts of problems. Even within a specific logical domain, such as conservation of amount, a particular child understands conservation of clay, for example, before conservation of liquid, instead of showing an integrated, coherent structure based on the concrete-operational logic of conservation.

While Piaget (1972) explicitly acknowledged the pervasiveness of unevenness, he never gave a satisfactory account of why children so often show such inconsistency. He preferred to focus on the logic of the mind rather than the variability in activities, and he gradually withdrew from investigating psychological processes, focusing instead on philosophical analysis (what he called "the epistemic" rather than the psychological). It was largely this discrepancy that led to the development of the neo-Piagetian approach, in which first Flavell and Pascual-Leone and later Case, Fischer, Halford, and others sought to reconcile Piaget's logical, stage-based approach with children's observed unevenness in level. These neo-Piagetians recruited explanations of change and variation processes from learning theory, information processing, and biology, among other places (Case, 1987; Case & Edelman, 1993)

Because the information processing approach concerns itself with the details of cognitive processing and change, including mental structures such as working-memory capacity, many researchers have looked to it to deal with the problem of variability in performance. In general, information processing strives to specify precisely the goal-oriented mental manipulation of bits of information in real time: Human cognition is analyzed through a set of universal information-processing structures rather than a set of logical structures (Lindsay & Norman, 1972; Siegler, 1991). In this approach, individual units of knowledge, some more procedural and some more declarative, are assimilated into higher-order knowledge structures, which can include organizational groupings such as categories, prototypes, event knowledge,

and scripts, or more functional groupings such as strategies, rules, and plans. The mind is conceived as much like a computer, which codes, recodes, and decodes information, stores and retrieves the relevant bits, combines and differentiates features, and brings some information into awareness. Children's development, according to this approach, is constrained by the "information they represent in a particular situation, how they operate on the information to achieve their goal, and how much information they can keep in mind at one time" (Siegler, 1991, p. 59). This approach infers children's mental problem-solving strategies from assessments such as their verbal reports, timing, effort, and errors (Siegler & Crowley, 1991). From these measures, it strives to explicate the flow of information through the mind, including qualitative shifts in the ways children think about problems. These shifts are usually treated in terms of flows in computer-like programs and not usually as stages.

Neo-Piagetians, including Case (1991), Fischer (1980b), Goldin-Meadow (1993), Halford (1987), and Siegler (1994), have drawn on the processes of change from the information processing school, incorporating them into constructivist approaches to study both the stage-like nature of development and the inescapable variability that characterizes learning. The result, most generally, is a view that with development children can simultaneously represent and mentally manipulate more pieces of information, or features of a problem, through a system-wide increase in their working memory capabilities. The increase involves not merely a larger number of items, but reorganization of simpler mental constructions into more complex ones that are built from the smaller pieces and shaped by individual and cultural environments.

Cognitive development, both in the long and short term, is the continual building of new knowledge by integrating, differentiating, and consolidating facts, concepts, skills, and relationships about the physical and social world according to culturally defined strategies. The variability in development can be analyzed and explained in terms of biological and maturational constraints, the nature of the knowledge domain and task, the immediate social and physical context, and the cultural context in which the knowledge is being acquired. This combination of insights has produced a general framework for the big picture of cognitive development, *combining concepts that were previously considered contradictory: the parallel, independent*

nature of skills in different domains combined with the similarity of growth processes across domains and a universal scale for cognitive development.

Developmental Webs: Unevenness and the Order in Variation

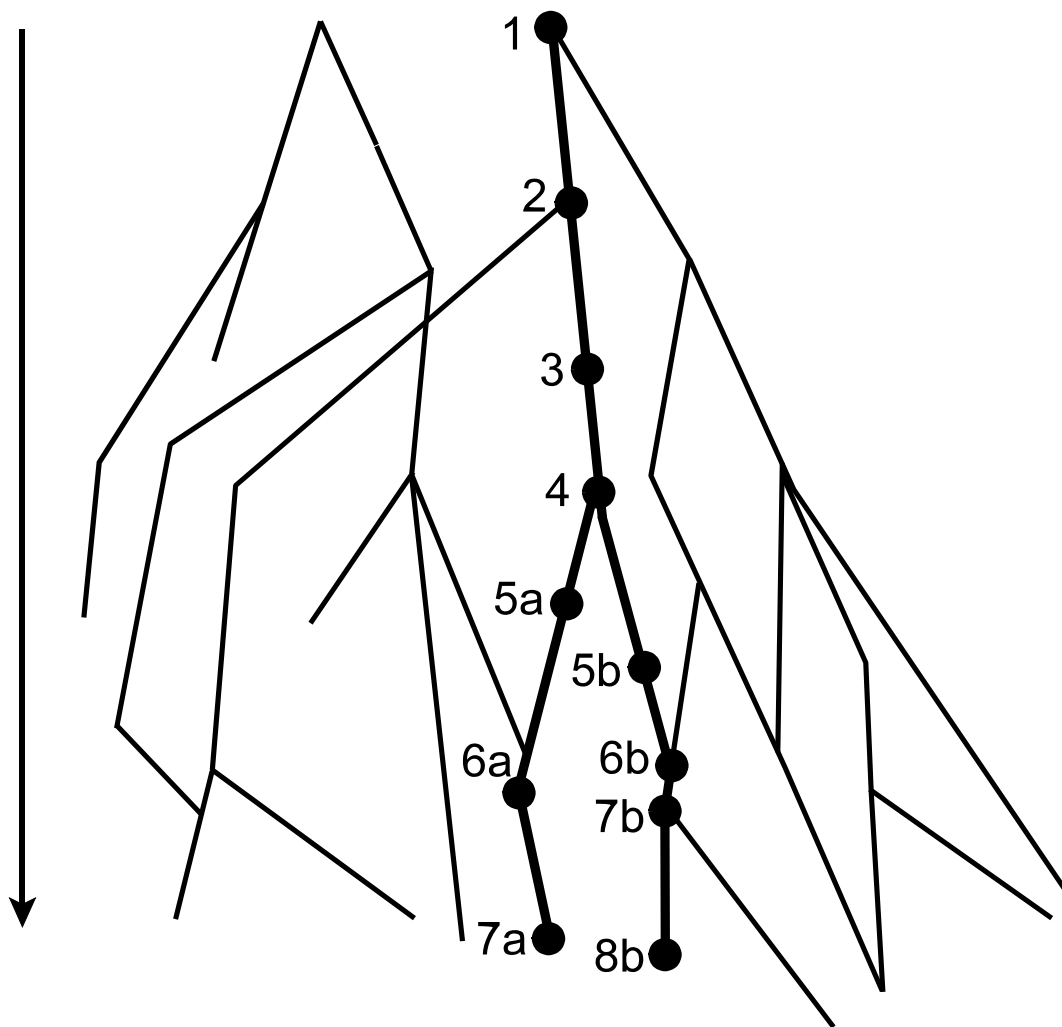
The focus on process and context in cognitive science has led to extensive documentation of the variability in children's understanding and behavior, especially unevenness in developmental level but also other kinds of variability within a child. The findings of pervasive variability have led many scholars to make the serious mistake of denying the existence of stages in cognitive development. When variability is built into assessments and analyzed, important principles of order become apparent in cognitive development and learning, and both the generality of developmental processes and the stage-like nature of growth become evident.

One important principle is that developmental sequences hold strongly within a task domain: When a set of tasks vary in complexity but have similar content, then developmental orderings are powerful and consistent (for example, Case, 1991; Fischer, Knight, & Van Parys, 1993; Fischer & Silvern, 1985; Halford, 1989; Keil, 1986; Turiel & Davidson, 1986). Their consistency provides a powerful tool for measuring development and analyzing processes of change. The specific orderings provide important assessments of theories of growth and learning. The sequences that Piaget described provide a powerful starting point, because they replicate consistently. He has proved to be an outstandingly accurate observer of children's development! His sequences fail only when task content and procedure are mixed within an assessment. When content and procedure are similar, Piaget's sequences replicate consistently.

Because of this combination of order within a domain and independence across domains, the general portrait of cognitive development shifts from the Piagetian ladder of stages that cut across domains to a different metaphor – a *web* of multiple, parallel strands (domains) that sometimes intersect or divide, as shown in Figure 1 (Fischer & Bidell, 1998; Fischer et al., 1993). In a constructive web, knowledge building does *not* proceed across all areas of development synchronously in a linear, ladder-like progression. Instead, individual skills, which

are represented by different strands of the web, develop independently within domains, proceeding largely at their own pace. Sometimes the skills in two strands split off to proceed independently or come together to reinforce each other, as when a beginning reader combines the independent strands for visual-graphic analysis of a written word with phonological analysis of that same word in speech (Knight & Fischer, 1992; Torgesen, Wagner, & Rashotte, 1994). Within each strand, a child develops skills in a tight sequence, which has some of the properties of a ladder, but with branching, as shown for the highlighted strand in Figure 1, which has dots for each step assessed along the strand. These tight sequences have led some researchers to the concept of module, a tightly organized domain of knowledge (Fodor, 1983; Gardner, 1983). Horizontally across the strands of the web, a child's skills are only loosely ordered, because domains involve parallel but independent abilities. The skills in a developmental web are independent, but at the same time they involve similar growth and brain processes. These similarities are what have led to so much confusion – why Piaget, Chomsky, and many other observers posited that a single coherent, logical structure produces the changes. However, the mixture of similarity and independence across domains has undermined these classic interpretations. The concept of *working memory* as a constraint on cognitive development illustrates the shift from universal structures to domain-specific ones.

Figure 1.
A Developmental Web with a Highlighted Strand



Development follows multiple, independent strands, which can branch or join. Each strand forms separate, parallel complexity scales. Most cognitive-developmental measures involve only one such scale, such as the one highlighted. The dots along the strand mark steps that are assessed.

Robbie Case (1980, 1985), building on Piaget, information processing, and the model of Pascual-Leone (1970), created an influential neo-Piagetian theory that explained cognitive development as involving increases in short-term memory or M-space: With age, the size of the buffer for short-term memory grew, starting with one item and gradually growing until it reached nine items. All activities were processed through this single buffer, which thus served as a bottleneck to explain children's limited early capacities and the gradual growth of those capacities with age and experience.

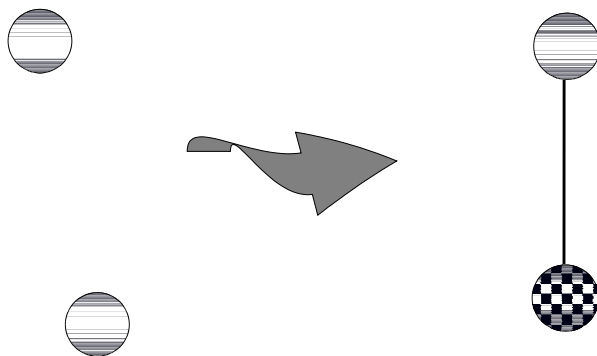
However, the evidence of unevenness and other kinds of within-person variability created insurmountable problems for the construct of short-term memory. On the one hand, a child of a given age did not show the same short-term memory capacity across all domains. On the other hand, development within a domain involved inexorable growth in the number of items that could be held in mind, and the numbers were similar across many domains, indicating a similar growth process. Consequently, Case (1991) and many other scientists changed the concept from short-term memory, which involves a single memory buffer for all domains, to working memory, which involves a similar process of memory across independent domains. Indeed, neural networks in the brain all show working memory, but that working memory takes different forms depending on the specific kind of network (Bachevalier, Malkova, & Beauregard, 1996; Grossberg, 1978; Grossberg, 1987; Mishkin, 1995).

The dynamic process of skill construction clearly involves some such change in working memory across domains, and more generally, processes of cognitive development look highly similar from one strand to another in the developmental web. At the same time, the specific skills are different and mostly independent between strands. That is why the web provides a better metaphor than the ladder for the nature of development.

Most generally, complex knowledge and skills develop through a process of coordination, in which higher-level skills are hierarchically built up from earlier skills through integration and differentiation (Bruner, 1973; Case, 1985; Case, 1991; Fischer, 1980b; Fischer & Bidell, 1998; Goldin-Meadow et al., 1993; Piaget, 1936/1952; Werner, 1957). In this

developmental process, which is similar to the chemical construction of atoms into molecules, a child carries out several activities (skills) at the same time in a context, and this co-occurrence induces differentiation and coordination, as illustrated in Figure 2. In reading a word, a child

Figure 2.
Transition Process:
Co-Occurrence Followed by Coordination &
Differentiation To Form a New Skill



References: Fischer & Bidell, 1998; Goldin-Meadow et al., 1993

looks at the visual representation, such as *dog*, and at the same time listens to the word. Development involves simultaneously differentiating and coordinating these two activities to form the skill for reading *dog*. Similarly in a Piagetian conservation task, a child sees low and high glasses for orange juice and judges that the amount of orange juice becomes less when the juice is poured from the high one to the low one. Then in a variation of the task a moment later, she sees

the low one as wider than the high (narrow) one. This co-occurrence initially involves a shift from one skill to another, which induces the child to explore the relation between the two skills, and she gradually constructs a new skill for conservation of orange juice.

The process of coordination and differentiation occurs broadly across all skill domains, and the rules for analyzing and predicting the process are similar in each domain (Fischer, 1980b). Just as atoms bond with other atoms to produce new substances, highly contextualized component skills are coordinated into new, more complex skills that control a more differentiated range of activities within the context or across previously unrelated contexts. As simpler, component skills are integrated and organized into new units of behavior and thought, they continue to function as subsystems, supporting the function of the new skill as a whole. For instance, a 10-year-old girl's skill for playing basketball relies on her effective integration and coordination of the component skills of walking, jumping, and eye-hand coordination. Likewise,

her skill for storytelling involves integrating skills that include pretending or imagining, understanding social categories, and representing socially reciprocal activities (Fischer & Bidell, 1998). In this way, skills are organized into multilevel hierarchies that can, in turn, be differentiated into their component parts and rebuilt to suit new contexts. These similar processes produce powerful ordering principles in skill hierarchies across domains in the developmental web. To fully capture the rich variability of human development requires focusing on the full range of variations in development, going beyond the rational, scientific skills that have been the focus of Piaget, Case, and most other neo-Piagetian scholars. We have formulated a framework of concepts and methods for analyzing these principles, called dynamic skill theory. As the name suggests, the approach has dual emphases – on *skills*, their organization and relationship to the social and emotional context, and on *dynamic constructivism*, in which skill organizations vary dynamically according to specifiable growth processes and control parameters (Fischer, 1980a; Fischer & Yan, 2002; Goldin-Meadow et al., 1993). This combination of approaches represents a way to simultaneously describe development as an overarching set of large-scale changes while keeping sight of the incremental, daily, even minute-to-minute dynamics that show much of the order within the variation. The goal is to unpack without dissecting, and to simplify and clarify in a useful way that does not over-specify. We will return to the concepts of dynamics and microdevelopment in the third section of the paper, where we present a close-up look at developmental processes at work.

To analyze behavior in context, we take skills as the primary unit of analysis. Different from concepts of ability, competence, capacity, intelligence, and scheme (Piaget, 1936/1952, 1937/1954, 1947/1950), skills are conceived of as both task-specific and context-dependent (Fischer & Bidell, 1998; van Geert, 1991; see also Young, Kulikowich, & Barab, 1997). Skills begin as highly specific to task and context, and through constructive generalization they can gradually be extended to multiple tasks and contexts. They are psychological structures that draw on and integrate multiple organismic and sociocultural factors, such as emotion, memory, planning, and cultural scripts, without introducing artificial boundaries between these natural

components of behavior and thought. For example, a 10-year-old girl's skill for storytelling draws on her pretending, her understanding of social roles and culturally defined scripts, her understanding of emotions and reciprocity in interactions, and more traditional cognitive processes, such as her ability to plan and remember her story. Likewise, she has other skills for playing basketball, coercing daddy into reading one more bedtime story, solving arithmetic problems, or being a supportive best friend.

The dynamics of development combine the many processes of change and variation to create webs of developing skills and activities. Understanding the order in the diversity of human development requires analyzing these dynamic processes. Skills depend on the biological maturation of body and brain, and simultaneously on the social and emotional contexts and conditions of the particular task and activity. Because these factors vary naturally, development across domains, even across closely related domains, does not show simple steps in a ladder but strands in a web, and different webs for different students. Indeed, researchers and educators can see the developmental order only by understanding these sources of natural variation.

Social Support and Developmental Range

One important and powerful source of variation is the climate of social support in which a child acts and learns, and this factor powerfully affects the child's apparent "competence" and explains an importance source of variability (unevenness). With a skilled, supportive adult or peer priming key parts of the task, a child produces a more complex level of storytelling than without that social support. For example, in a high support assessment an adult can model a high complexity story and ask a 10-year-old girl to tell a similar one, while in a low support one the adult provides no direct modeling. Likewise, a first-grade boy can sound out and suggest rhymes for words only when his teacher helps him by providing a choice of words that rhyme or by modeling the skill of sounding out (Fischer & Rose, 2001; Knight & Fischer, 1992). Well designed artifacts such as a text, diagram, or computer program can provide similar support. The variation between supported and unsupported conditions – which we call *developmental range* – does not surprise anyone who works with children, but it turns out to be essential in

understanding the order behind the variations in development that have led to century-long debates about whether cognitive development occurs in stages.

Lev Vygotsky (1978), the great Russian psychologist, understood the importance of variability with social support. He proposed that human cognitive development involves the internalization of species-specific problem solving through the acquisition of culture and language and that inherent to this internalization are social support and a range or zone of skill. Vygotsky emphasized how social interactions between experts and novices drive cognitive and language development, with adults and older children naturally acting as experts to provide support for younger child-novices. He explained that children's proficiencies vary systematically as a function of this support, increasing as problem solving is socially scaffolded and decreasing as a child struggles on his own to integrate new cognitive strategies into his independent thought and action. Specific social context and culture are thus essential contributors to individual cognitive development.

A Universal Developmental Scale But Not Universal Skills

This major principle of variation in children's performance provides the solution to the stage debate: Stages do indeed appear in some aspects of cognitive development, but they result from the dynamics of growth within and across strands in the web, not from universal cognitive structures. When children's problem solving is analyzed according to support and its related changes in performance, the stage debate disappears. Development has strongly stage-like properties under conditions of high support, but not under conditions of low support. From this insight flows discovery of a universal developmental scale for skill complexity that applies to all the strands in a developmental web, even though the strands develop independently. This complexity scale is evident across domains, methods, and laboratories from infancy through early adulthood (Dawson, in press; Fischer & Bidell, 1998; Fischer & Rose, 1996; McCall, Eichorn, & Hogarty, 1977; van Geert, 1998). The universal scale provides a powerful tool for developmental and educational assessment!

People acquire skills in a developmental range in which their competencies vary as a function of support, among other factors. Skills are not all or none: A person does not suddenly

move from not being able to perform a task to performing it well. Instead, a person's skills vary frequently between two upper limits – a *functional level*, the most complex performance that a child or adult performs without support, and an *optimal level*, the most complex performance that she or he performs with explicit support, such as through modeling or priming (see Fischer & Bidell, 1998 for a more complete description). As a person builds a more competent, automated skill, she no longer requires extensive support, and can routinely perform well at a functional level. For example, driving a car may at first require guidance and full concentration, but eventually it becomes almost automatic under most circumstances. Note that a dramatic change in the context in which a skill is being performed, such as a blizzard, highly emotional car conversation, or a change of vehicle from a sports car to a large truck, may require that the person drop back temporarily to a lower level and build up a more complex skill anew.

While functional skills typically show no stage-like pattern of growth, changing smoothly or with inconsistent jumps, optimal skills show a consistent series of discontinuities – spurts, drops, and qualitative changes across domains. That is, children show a series of qualitative shifts in skill organization, especially in optimal performance of their most complex activities, and for familiar domains such as those taught in school, these shifts usually occur within a specific age range for each new developmental level. Across domains (strands in the web), these changes make up the large, empirically observable shifts in thinking and acting that we see throughout childhood and adolescence, which are called *developmental levels*.

Take, for example, the development of abstract concepts for arithmetic operations (addition, subtraction, multiplication, and division) in 9- to 20-year-olds. A study of understanding relations between pairs of arithmetic concepts demonstrates both the role of high support in the coordination of skills and the stage-like nature of development in a high-support context (Fischer & Kenny, 1986). Students sat with an interviewer and solved a series of simple arithmetic problems and then used those problems to explain the relations between pairs of similar arithmetic operations (addition and subtraction, addition and multiplication, subtraction and division, and multiplication and division). This task was performed first under a low support condition, in which the experimenter simply asked the student to explain each relation, and then

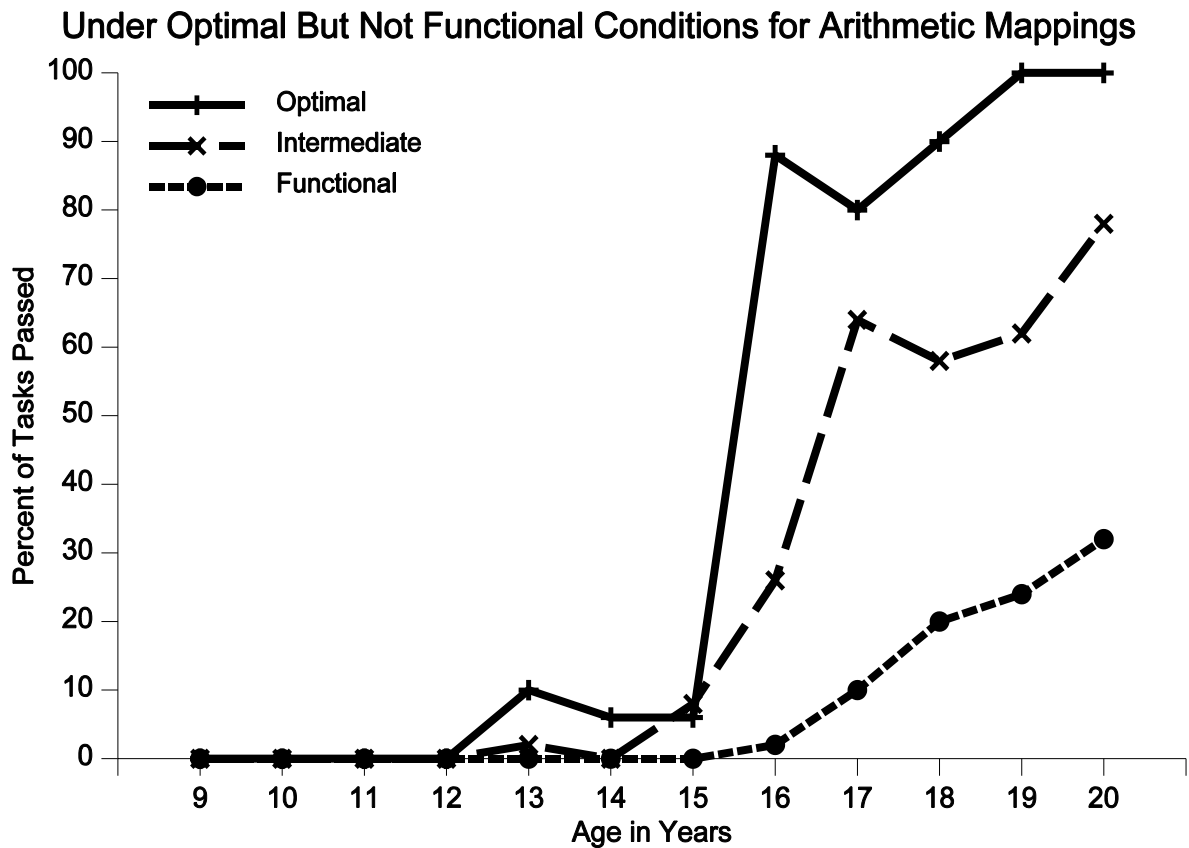
under a high support condition, in which the experimenter primed all of the key ideas through showing the student an example of an appropriately complex answer. These two conditions were then repeated two weeks later, to give the adolescent time to practice with the problems. Students had to produce a true abstract explanation, going beyond a concrete, problem-specific answer, such as "Addition and subtraction relate in these problems because $8-3=5$ and $5+3=8$." Instead, they needed to explain the relation in general, abstract terms and then apply the explanation to the concrete problems, such as "Addition and subtraction relate because in addition, you put together numbers, while in subtraction, you take numbers back apart. So addition and subtraction are opposites. In this problem, you are putting together the 5 and 3 in addition, and then taking them back apart in subtraction."

Low-support performance (functional level) improved gradually with age and never climbed very high, as shown in Figure 3, but high-support performance (optimal level) was consistently higher and showed a distinct spurt at age 16 that was remarkably consistent across students. This trend in optimal level performance was especially evident after practice: At ages 13 to 15 most students failed to understand all the arithmetic relations, and even with high support and practice only a few understood one of the relations. Performance spurted dramatically starting at age 16, when every student understood a majority of the relations. In the low-support, functional level condition, no such spurt occurred, and only one 16-year-old understood one of the relations.

Similar, powerful spurts have been demonstrated across several domains and age ranges in several cultures, including reflective judgment (Kitchener, Lynch, Fischer, & Wood, 1993), moral reasoning (Dawson, in press; Dawson, Commons, & Wilson, 2001, submitted), self understanding in the United States, China, and Korea (Fischer & Kennedy, 1997), and others. Across familiar tasks, optimal level skills spurt suddenly to much higher levels within a narrow age zone, which include the ages that Piaget posited for his four main stages as well as additional levels. A more complete description of these discontinuities, which we call levels and tiers, is presented elsewhere (Dawson et al., 2001, submitted; Fischer & Bidell, 1998; Fischer & Bullock, 1984; Fischer & Farrar, 1987), but we will present an overview here.

Evidence clearly shows the existence of at least ten developmental levels (and also suggests three additional levels in early infancy, where the data are more sparse). The levels were predicted by skill theory (Fischer, 1980b), and they have been corroborated by multiple assessments of discontinuities, ranging from simple spurts like that in Figure 3 to gaps in developmental scales based on Rasch analysis of interview data over a wide age range (Dawson et al., 2001, submitted). The close relationships of the emergence of levels to children's ages supports a common observation. Adults familiar with the cognitive and emotional development of children can accurately estimate a child's age from a description of their best performance in a few different situations. Developmental levels provide the cognitive basis for the accuracy of these intuitive assessments!

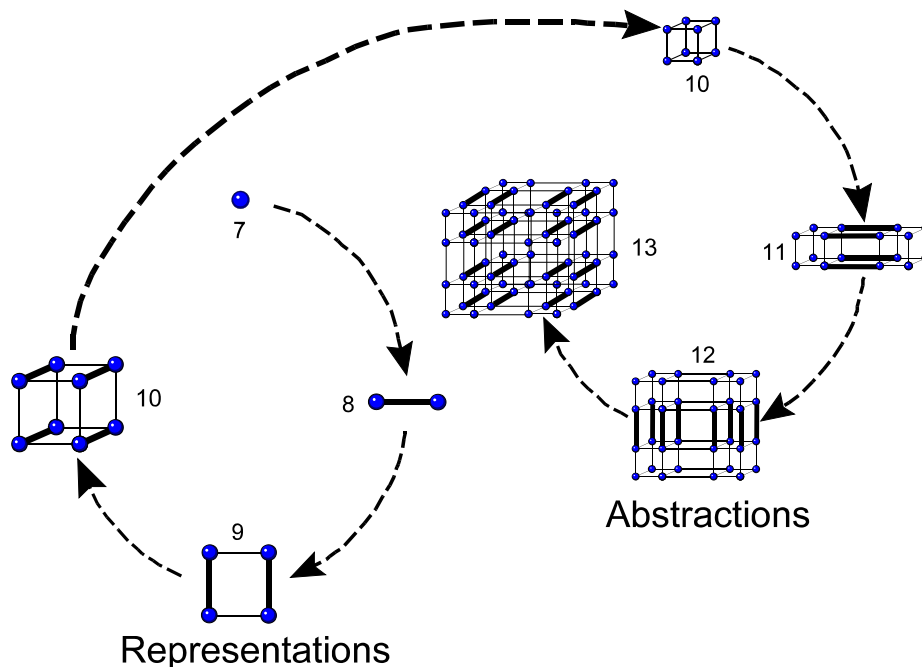
Figure 3. Spurt for a New Level



Optimal level is assessed with high support and practice (Session 2 Support), functional level without support or practice (Session 1 No Support). The intermediate condition involved high support but not practice (Session 1 Support). Reference: (Fischer, Kenny, & Pipp, 1990)

According to the dynamic skills framework, the thirteen levels are organized into four large cycles called tiers: reflex actions, sensorimotor actions, representations, and abstractions. Some empirical evidence supports the separate tiers, but further research is required to test this hypothesis. Figure 4 illustrates the growth cycles for the tiers involving representations and abstractions, which are the most relevant to the school years, developing between the preschool years and early adulthood. Within each tier, component skills are reorganized into a new level four times (a cycle within a cycle) with the last major reorganization forming the first level of the next tier (hence four tiers of four levels make a total of thirteen levels). Each reorganization involves coordination and differentiation of skills to create a new more complex skill that forms a unit at the next level. In each successive tier, the reorganization of skills into

Figure 4. Cycles for Development of Levels of Representations and Abstractions on the Universal Complexity Scale



The complexity scale has 13 levels, including the last seven shown here, forming two growth cycles – one for representational levels and one for abstract levels. These levels first emerge between 2 and 25 years of age.

levels follows a similar trajectory, but the skill units coordinated are more complex in that they are built from the units of the previous tier. The building blocks in Figures 2 and 4 are metaphors for actual skill structures, which are analyzed through formulas that specify components and relations between them.

The first level in a tier involves single units, such as single actions or representations or single abstractions. Examples of single abstractions include the general concept of addition, [ADDITION], as well as each of the other arithmetic operations, and these emerge under optimal conditions at approximately 10 years of age. However, these students cannot coordinate the operations into relations. At the second level of mappings, a student maps or relates two units, such as actions in infancy, representations in later childhood, or abstractions in adolescence. The relations of arithmetic operations assessed in Figure 3 are mappings of abstractions, such as addition and subtraction as combining versus separating numbers,

[$\begin{array}{c} \text{ADDITION} \\ \text{COMBINING} \end{array} \text{ — } \begin{array}{c} \text{SUBTRACTION} \\ \text{SEPARATING} \end{array}$]. At the third level of systems, a student relates

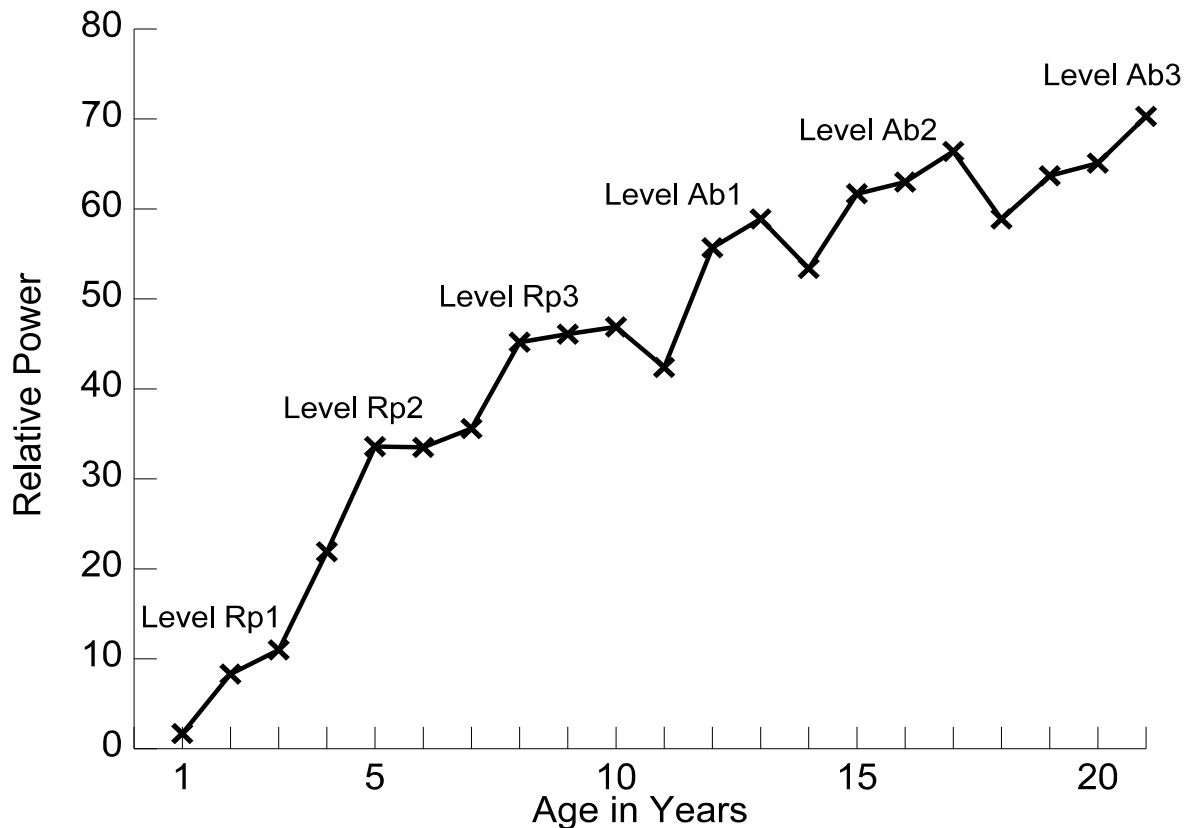
independent pairs of mappings to form a system relating several aspects of two abstractions, such as types of number grouping (groups versus single numbers) and types of number combination (combining versus separating numbers) to relate multiplication and subtraction,

[$\begin{array}{c} \text{GROUPS} \\ \text{MULTIPLICATION} \\ \text{COMBINING} \end{array} \longleftrightarrow \begin{array}{c} \text{SINGLE NUMBERS} \\ \text{SUBTRACTION} \\ \text{SEPARATING} \end{array}$]. The fourth level involves integration of

systems of skills to form a system of systems, which is also a single skill unit of the next tier. For example, a 10-year-old coordinates representational systems for two specific subtraction problems, such as $9 - 5 = 7$ and $103 - 54 = 49$, to create a single abstraction for subtraction as separating numbers.

One of the most exciting discoveries of the last decade is that development of brain activity demonstrates reorganizations that parallel the skill levels, suggesting a neurological basis for the cognitive discontinuities observed in optimal level performance (Fischer & Bidell,

Figure 5. A Series of Spurts in Development of Relative Energy in EEG



Relative energy was assessed for the alpha frequency band in the occipital/parietal area of the cortex. Reference: Matousek & Petersén, 1973

1998). The richest evidence involves brain electrical activity (the electroencephalogram, or EEG), although suggestive evidence also exists for synaptic density, myelin, and brain volume (Chugani, 1994; Fischer & Rose, 1994; Huttenlocher, 1994; Thatcher, 1994). For EEG both the energy in the waves (relative power) and the connections among cortical regions (measured by coherence – correlations among waves) develop through a series of discontinuities (spurts and shifting patterns) at particular ages that closely correlate with the ages for cognitive levels.

Figure 5 shows the first study demonstrating such discontinuities (Matousek & Petersén, 1973):

The energy in the waves at the back of the cortex shows a series of spurts and plateaus that

closely parallel the levels for representations and abstractions through age 20. What's more, these spurts in activity appear to cycle around the brain in systematic ways for each tier, starting with a spurt in frontal EEG power to mark the start of each tier, perhaps providing prefrontal support for the formation of the new skill units that begin a new tier. Then spurts in energy continue around the cortex, moving with each level systematically from frontal to occipital-parietal, to central and temporal and from right hemisphere to left until they return to the frontal cortex to begin another tier (Fischer & Rose, 1994, 1996). While very little research has tested developmental relationships between cognitive growth and brain growth in the same children, the apparent parallels between brain and skill development are exciting and suggest the possibility of a major advance in understanding brain bases for cognitive development. Brain development seems to involve a recurring growth cycle of neural networks and learning, in which a child learns skills and concepts not only once, but also relearns and reworks them anew at each successive optimal level.

Although the historical search for a universal cognitive structure based in logic across domains has proven fruitless, the evidence for a common complexity scale for development provides a powerful tool for advancing developmental and educational research. What cognitive scientists have uncovered is not a common structure or logic, but a common broad scale that is based in the ways that skills are built and reorganized. Having one scale that can be used for measuring the wide range of human skills and activities brings together theory with method in a particularly fruitful way, enabling the use of the same scale for studying the variability of cognitive development and learning. Instead of artificially simplifying the social, emotional, and cultural context in which children function, researchers can devise contextually appropriate assessments while maintaining a common scale to compare skills and activities across those assessments.

As a result, what have seemed to be disparate, conflicting approaches to cognitive development become compatible and integrated. Concepts of developmental stages and levels come together with concepts of natural variation in development. Research on developmental levels can facilitate analysis of variability instead of contradicting it. Building a meaningful theory

of development in cognitive science and education involves going beyond assessment of allegedly stable cognitive competencies to the study of principles of variation in cognition, emotion, and action in natural contexts.

The Middle View: General Structures for Broad Domains

Cognitive scientists have not limited themselves to searching for totally universal mental structures that produce generalization independent of content. They have also launched an extensive, continuing search for intermediate structures that produce generalization within a domain. If logic does not pervade the mind, then perhaps a more modest general structure might pervade a domain of the mind. Perhaps there is, for example, a general structure for taking other people's perspectives, or a general structure for understanding other people's minds. What a great tool for educators if children could learn a single structure to improve their skills across a wide array of tasks in a domain! Unfortunately, like the search for universals, this effort to find domain-specific general structures has been mostly unsuccessful, although it has produced many interesting and important findings and methods. Instead, recent discoveries suggest that success may depend on a shift in framework similar to the one that led to discovering the universal scale for developmental complexity. The key seems to be to shift the search from foundations in logic to foundations in cultural and linguistic contexts, grounded in principles of variation.

The Long Search for Domain-Specific Structures for Generalization

The search for domain-specific general structures has persisted for over fifty years, as scientists have moved through a series of hypotheses about plausible general structures. In the mid-twentieth century the search focused on *perspective-taking*, also called role-taking, led by John Flavell (1968) with important contributions from Loevinger (1976), Feffer (1960), Kohlberg (1969), Chandler (1973), and Selman (1980). All these scientists and many others hypothesized a general structure for comparing and contrasting one's own viewpoint with that of another. From his earliest works Piaget (1932) emphasized the importance of perspective-taking in development from the preschool to the school years. Two- and three-year-old children are notoriously egocentric, frequently assuming unconsciously that other people share their

viewpoint: Since Susie loves Grandma, of course her new friend Rachel will also love Grandma. Since Lukas wants a dump-truck for his birthday, of course that is also what Daddy wants. Piaget described how by age 7 or 8 this egocentrism gives way to skilled perspective-taking: Children become skilled at comparing their own concrete perspectives – what they want, like, see, hear, and feel – with the perspectives of others, recognizing what is the same and what is different.

The many studies of perspective-taking clearly showed similar developmental trajectories across content areas, but a child's skill level in perspective-taking in one domain (one strand in the web) did not effectively predict the level in a different domain. The ability to take a friend's perspective in a social conflict, for example, did not relate to the ability to take someone's perspective in a game or in a moral dilemma. Despite this failure of cross-domain prediction, important research and intervention programs have grown from perspective-taking research, such as Loevinger's (1976) analysis of ego development, which enjoys widespread clinical use, and Selman's (1980) analysis of perspective-taking among peers, which relates to interventions with behavior problems in youths. Still, researchers have mostly abandoned the search for a single structure of perspective-taking that generalizes across many tasks and situations.

The failure to find a generalized structure for perspective-taking did not stop the search for domain-specific general structures, however. Flavell and his students moved the search to other hypothesized structures. After perspective-taking came metamemory, then metacognition, and then theory of mind, among others. The way people use their memory to recall things and to solve problems (*metamemory*) seemed a plausible candidate (Wellman, 1983): Surely strategies for remembering would generalize from one situation to another. *Metacognition* was another good candidate: Using a specific strategy for understanding, learning, or solving problems, it seemed, might generalize across situations (Flavell, 1979; Kitchener, 1983). Many teachers would like to be able to teach critical thinking or reflective judgment so that those skills could be generalized across all the subjects in the school curriculum.

The results were the same as with perspective-taking: Assessment of meta-x in one

situation predicts modestly at best to diverse tasks and situations. Consequently, research on metamemory and metacognition have dropped off, even more than research on perspective-taking, as cognitive scientists have mostly abandoned these hypothesized domain-specific general structures for knowledge.

The most recent primary candidate is *theory of mind* (Baron-Cohen, Leslie, & Frith, 1985; Leslie, 1987), which is a return to perspective-taking in a different guise: Children are hypothesized to develop a theory of other people's minds at about age 4, a change that is supposed to pervade children's social interactions and understandings. In contrast, children with autism are hypothesized to have a specific deficit in theory of mind, which prevents them from developing an understanding of other people's perspectives and emotions.

This area remains popular among cognitive scientists, at least in part because of the linkage with autism and the hypothesis of emergence at age 4, which is several years younger than the onset of perspective-taking at about age 7 described by Piaget. There are now scores of demonstrations that at about age 4 normal children (but not those with autism) develop skills for taking into account other people's knowledge when it contrasts with the child's own knowledge.

However, if theory of mind were in fact a generalized, domain-specific knowledge structure, it would need to predict substantial correlations between skills across domains involving theory of mind, but not between theory of mind skills and other domains that develop in the same age period, such as conservation of liquid or classification of blocks (Detterman, 1993; Fischer & Farrar, 1987). In fact, relating one's own knowledge to someone else's – a key component in assessments of theory of mind – is one of many skills that develop at age 4. Others include predicting how the height of a liquid will change when it is poured into a container of a different shape, relating one dimension for classifying blocks to another (such as shape and color), and mapping numbers onto each other along a primitive number line. Clearly, emergence at age 4 is not a clear test of the generality of a module for theory of mind.

Therefore, interesting as these findings are, we suggest a broader explanation: that a general developmental reorganization emerges at age 4, as children develop the

representational mappings that underlie all these capacities (Case & Khanna, 1981; Fischer, 1980b; Fischer & Rose, 1994; Frye, Zelazo, & Palfai, 1995). To date, findings indicate only modest generality for theory of mind tasks, just like other age-related developmental correlations. As we have seen before, separate strands in the developmental web show similar ages of emergence of new cognitive levels; but independent of age, developments across strands are weakly correlated.

Finding Generalization across Tasks

The difficulty of finding generalization across tasks extends far beyond research on hypothesized domain-specific structures such as perspective-taking, meta-memory, and theory of mind. Cognitive scientists and educators have done extensive research on how a learned skill generalizes across tasks, not only in human beings but also in animals. Contrary to the common expectation that knowledge generalizes readily, researchers have had great difficulty finding generalization beyond very similar tasks. What occurs readily is near generalization, in which a student performs a task that differs modestly from the one where she learned the skill. For example, an 8-year-old boy who learns to tell a joke about a doctor examining a patient for a cold can typically generalize to tell a joke about a doctor examining a patient for flu or chicken pox, but he does not easily generalize to make jokes about chemists in their laboratories or generals with their soldiers. Educational assessments indicate that students who perform well in a class typically generalize their knowledge only to material similar to what was explicitly taught in the class. They do not show far generalization to distinctly different material. For instance, students taught a set of related concepts (a simple framework or metaphor) in science class, such as how genes specify characteristics of an organism, typically cannot generalize the framework effectively, erroneously using superficial similarities to generalize rather than deep ones (Dunbar, in press, 2001).

The generalization about generalization is that near generalization is to be expected, but far generalization to very different tasks and situations does not usually occur (Fischer & Farrar, 1987; Salomon & Perkins, 1989). The pervasive failure to find far generalization has led many cognitive scientists to pessimistic assessments about the possibility of far generalization

(Detterman, 1993; Shepard, 1987; Stevens, 1999).

Fortunately, a broader view gives a less bleak portrait. The key is to examine frameworks and concepts that students commonly use instead of those they learn in science class. Typically, students who cannot generalize the frameworks and concepts that they learn in school can easily generalize their own favored frameworks and concepts (Blanchette & Dunbar, 2000; Dunbar, in press, 2001). This difference stems from the process by which generalization takes place: To be generalized, a skill must be worked and reworked repeatedly over a long period with different tasks and contents – a process that people have done with their own favored skills. For someone to become an expert in a new discipline or profession generally requires five to ten years of learning (Gardner, 1993, 1999). Similarly, for students to generalize new knowledge requires either instruction based on their own familiar ways of thinking or extensive, long-term practice at using the knowledge in diverse tasks over long time periods, well beyond the time of the usual learning experiment and even beyond the length of a course in school. As currently taught, one course or one experimental intervention will not produce immediate generalized learning of new concepts and frameworks.

From this research, implications for domain-specific conceptual structures are straightforward: *For the structures to become generalized, either students must learn them extensively over long periods involving diverse tasks, or instruction must be grounded in common frameworks and concepts that are part of students' prior knowledge base.*

Finally, A Success: Case's Central Conceptual Structure for Number

Recently, the search for domain-specific general structures has scored a big success: Robbie Case and his colleagues have described what they call a *central conceptual structure* for number in early childhood, and it has shown powerful generalization across diverse domains (strands in the web) (Case, 1998; Case, Okamoto, with Griffin, McKeough, Bleiker, Henderson, et al., 1996). They conceptualize the central conceptual structure as a general schema that children construct for the number line, as shown in Figure 6, which develops from the coordination of two earlier schemas – one for global quantity and one for counting.

Case's form of neo-Piagetian structuralism strives to study and understand mental structures, or "core conceptual elements," as grounded in the cultural and linguistic frames that define specific knowledge domains (Case et al., 1996, p.5). Case's studies of children's adoption and use of culturally defined knowledge structures have allowed him to effectively explore the ways that knowledge compares and generalizes within and across domains – how particular tasks feed into children's broad, domain-specific capacities, which he calls central conceptual structures.

Based on this framework, Case and his colleagues devised a curriculum for teaching the number line framework to children in preschool, kindergarten, and early elementary school. An intervention as brief as ten weeks produced generalized improvement in number tasks across

domains, going well beyond the curricular tasks to

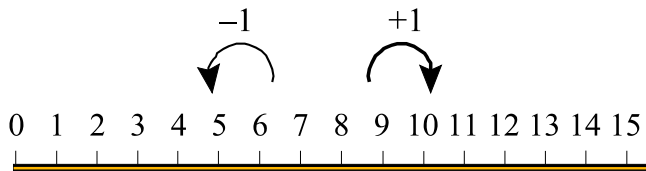
include tasks outside the content taught. For

example, understanding improved for not only

number tasks taught in the curriculum but also tasks

about musical scales (which are based in number) and

Figure 6.
Simple Number Line, Foundation for a Central Conceptual Structure



The metaphor of a number line forms the foundation for the central conceptual structure for number. In this simple version, adding 1 moves the number higher and to the right, and subtracting 1 moves it lower and to the left.

distribution of presents at birthday parties. In contrast, tasks about contents not involving number, such as social narratives, were not affected. Especially exciting were the size of the effects, which unlike many educational interventions were substantial, accounting for as much as 50 percent of the variance in students' performance over time. The interventions also succeeded in diverse nations and languages, including not only the United States and Canada but also Japan (Case et al., 1996). Here was success in the search for a domain-specific cognitive structure that generalizes powerfully.

Before Case himself died in the spring of 2000, he had laid the foundations for extending

the mathematics curriculum to later grades, and had also proposed searching for central conceptual structures in other domains, such as narrative and spatial representation (Case, 1998). His colleagues now continue his work, suggesting that the later central conceptual structures for number build upon Case's original number line to create more complex schemas, such as coordination of multiple quantitative dimensions (hours and minutes, feet and seconds, eventually x and y variables on a graph). The Case group's work is featured in a book to be published by the National Academy of Sciences, How people learn: A target report for teachers, on how learning can be improved in schools. An important question, however, is why he and his colleagues had such strong success in finding a general conceptual structure for a domain, in contrast to prior researchers.

Structures Grounded in Activity, Culture, and Language

The central conceptual structure for number is grounded in children's skills and contexts in a way that prior hypotheses about domain-specific general structures were not. First, Case grounded his analysis in what children actually do in counting and dealing with quantity. He, Sharon Griffin, and their colleagues took pains to make sure that the children's activities were connected to what the children already understood about number, in contrast with work in science education that assumes that children's ideas are simply wrong and must be stamped out (Carey, 1985). By building on children's existing well-learned skills, the curriculum could produce faster generalization of new knowledge instead of requiring the very long periods for mastery that totally new frameworks and metaphors demand.

Second, the number line and related concepts are grounded centrally in the languages and cultural practices of the children receiving the curriculum. Case did not emphasize this fact, but we suggest that it is essential to his success. The curriculum for teaching the central conceptual structure for number took advantage of the metaphoric structures for number in everyday language and cultural practices. Cognitive linguists led by Lakoff and Johnson (1980) have identified hundreds of metaphoric frameworks that are embedded in everyday speech, which speakers learn implicitly by learning a language and its associated cultural practices. Some of these metaphors are common across languages, including the number line, which is

embedded in English, Japanese, and many other languages. It shapes people's sentences, their gestures, and many of their communications and joint activities. For example, people routinely use their hands to mark off numbers on a number line as they speak, and they speak metaphorically using "up" and "down" to represent adding and subtracting. Lakoff and Núñez (2000) go far beyond the number line to lay out the metaphoric structures in the language of mathematics, but more important for effective instruction in schools are the central conceptual structures that are embedded in ordinary language.

For example, motion along a line is a pervasive metaphoric structure in human languages, going far beyond number and probably facilitating generalization of such a metaphor in Case's curriculum. Most languages use travel along the line of a journey to represent events in time: "Graduation is coming up." "I was so busy that Graduation just passed me by." "I am fast approaching the deadline for this paper." "I missed the deadline for this paper." "The deadline for this paper whizzed past long ago." The event can be traveling toward the person, or the person can be traveling toward the event; but in either case movement along a travel line is the assumed framework for events in time, just as the number line is the assumed framework for arithmetic operations with number.

Cognitive science and education can benefit greatly from discovering other central conceptual structures besides number that are essential to students' learning and that can be taught to improve knowledge. Key in this search is to formulate hypothesized central conceptual structures that are grounded in students' skills and in their linguistic and cultural practices, so that educators can help students to learn to use the structures more effectively and generalize them broadly across domains. This linguistic-cultural grounding contrasts with the origin in logic of most hypothesized domain-specific general structures, such as metacognition and theory of mind. We suggest that a great starting point is the hundreds of metaphoric frameworks described by cognitive linguists based on people's everyday language. Embedded in language and associated cultural practices, these metaphors provide a powerful set of candidates for central conceptual structures (<http://cogsci.berkeley.edu/MetaphorHome.html>).

We believe, as did Case, that perspective-taking and theory of mind are good

candidates for such structures (Case, 1998; Fischer & Watson, 2001; Watson & Fischer, 1980). To avoid the problems of previous research, scientists and educators must redefine the hypothesized structures to build on the grounded metaphors of language and culture. In one study of perspective-taking, Samuel Rose (1991/1990) did a careful task and contextual analysis of multiple perspective-taking tasks involving diverse content and found strong correlations across tasks independent of age. The hypothesized domain-specific general structures for perspective-taking and theory of mind may yet prove to exist, provided that researchers conceptualize them as grounded in linguistic and cultural practices within a framework based on variation. Discovery of additional central conceptual structures requires combining specific examination of children's actual skills with a framework for analyzing the variability that children routinely show from context, language, and culture.

The View Up Close: Microdevelopmental Analysis of Learning –

Building a New Paradigm for Cognitive and Educational Research

Learning and teaching are at the center of education. A fundamental set of questions in cognitive science throughout its history have been: How do learning and development occur? What are the mechanisms of change, and how can we trace them? What are the pathways to effective learning, especially in educationally important domains such as reading and mathematics? How and when do people use skills from one specific task when they face a related task? How do people build up central conceptual structures from diverse skills? These basic questions are essential to illuminating the ways that people build generalizable as well as more specific knowledge, but they have been difficult to answer because of limits in methods and theories about learning and development. Now those limits are fading away with the new tools and possibilities of twenty-first century cognitive science, enabling scientists and educators to track how people build, use, and generalize knowledge in real-world settings such as classrooms by studying variation in short-term psychological change, or *microdevelopment*.

Developmental scholars have long recognized the importance of analyzing the processes of change that lead to development over short time periods, and more generally integrating short-term learning and long-term development within a single framework (Bruner,

1970; Estes, 1955; Hebb, 1949; Piaget, 1936/1952; Werner, 1957). Only now have cognitive-scientific discoveries and new technology made it possible to realize these goals by recording and supporting ongoing learning in everyday environments. Analyzing learning and development by studying mechanisms of change in real-time behavior and problem solving is especially relevant to education: The new methods and concepts provide powerful tools for assessing individual learning and curricular effectiveness, designing learning environments, and individualizing assessment and instruction to optimize students' long-term growth.

Much research has been devoted to studying mechanisms of change, especially motivated by learning theory (Estes, 1955; Hull, 1952), information processing (Lindsay & Norman, 1972; Shiffrin & Schneider, 1977), and neural networks (Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996; Grossberg, 1987), but it has been mostly restricted to narrow aspects of behavior studied in laboratories and other highly controlled environments. Until recently the limits have been severe on analysis of learning in real-life contexts, such as classrooms and playgrounds. Researchers have tried to investigate these situations, but because of the inadequacies of available methods, their results have been confined primarily to providing interesting case studies. They have not been able to build cumulative knowledge about processes of learning and development of skills and understanding in natural settings.

At the beginning of the twenty-first century the situation has changed radically, so that it is now possible to study learning, problem-solving, and related processes in classrooms and to build strong scientific theory about the nature of learning and development in real-life contexts. A number of investigators recognize this new possibility, as reflected in two important new books. Microdevelopment (Cambridge University Press), edited by Granott and Parziale, brings together most of the important cognitive scientists who are using microdevelopment to open up the study of learning and development. Knowing What Students Know, edited by Pellegrino, Chudowsky, and Glaser and written by a panel of the National Academy of Sciences, describes how educational assessment can be used to both study and improve education. Researchers and educators can begin to analyze individual learning and development, tracing the variations and systematic changes in a student's skills and building specific, precise models of how they

have learned in the past so as to predict how they will learn in the future. Educators can use assessment for formative evaluation, to improve their own teaching and their students' learning as their programs are being formulated and put into practice (Shepard, 2002). The potential for predicting and improving learning and development is enormous!

The reasons for the new situation start with the insights of cognitive science concerning the web-like nature of cognitive development, the common scale for complexity underlying change in different domains as well as other powerful new assessment tools, and the nature of broad domain-specific structures of knowledge. These tools and concepts provide the building blocks for using microdevelopmental methods to study development and learning in a way that will lead to cumulative knowledge and provide the foundation for understanding learning in schools and other educational settings. The use of computers in classrooms can facilitate these analyses of ongoing learning, both facilitating learning and recording it. New tools to build explicit models of individual learning pathways can greatly increase the power and precision of cognitive theories and educational supports.

Analyzing Processes of Change

In microdevelopmental analysis, individual growth curves are analyzed, not combinations of standardized data from many students (Granott & Parziale, in press; Siegler & Crowley, 1991; Yan & Fischer, 2002, in press). Changes in learning and generalization can be analyzed and compared across skills and tasks, tracing for example the progress of generalization of new knowledge to different tasks and contents by individual students or small groups. Commonly the progress of learning can be directly detected, including the nature of construction of a more complex skill and the generalization of that skill to new situations. The general complexity scale illustrated in Figure 4 greatly facilitates the research by providing a common scale for comparison of diverse skills.

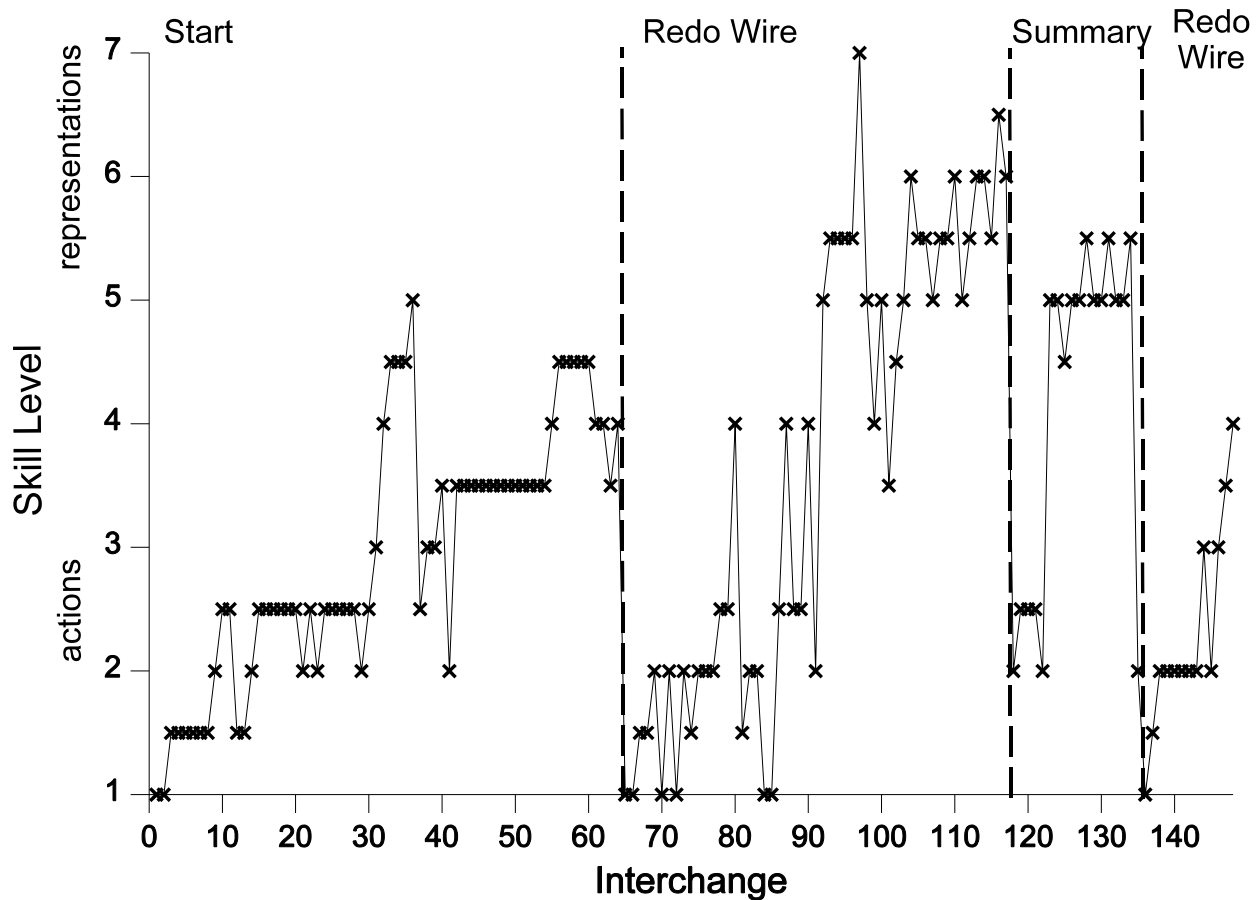
Shapes of Learning. A key tool for analysis is the shapes of growth in learning and problem-solving. In everyday learning activities, people produce complex growth patterns, with activities that differ widely in level of complexity, varying from moment to moment within a range that does not show simple upward progression (Estes, 1955; Fischer, 1980a; Yan & Fischer,

2002, in press). Fifty years ago, cognitive scientists rejected these complex curves as not showing “real” learning (Fischer & Yan, in press), but with the insights of dynamic systems theory, current cognitive scientists recognize that complex trajectories capture the true shapes of learning and development. No real-time trajectory moves along a straight line, but instead each one fluctuates up and down within a range that reflects constraints.

Growth curves show how people generalize a new skill by repeatedly rebuilding it in a robust wave-like pattern of construction and reconstruction rather than in a straight line pattern or even a linear progressive trend. Figure 7 illustrates how a dyad of graduate students learned a new skill in a study by Nira Granott (Granott, 1994, in press). The dyad of Ann and Donald worked with a lego robot that changed its movement in response to light. (The study was done before lego robots were available in toy stores, when they were still under development at the Media Laboratory at MIT.) Ann and Donald knew nothing about how the robot worked or what it responded to. They tried to figure out what it was and how it functioned. Beginning at a very low level of complexity in understanding the robot, they worked closely together over a period of half an hour to gradually build a more complex shared understanding of the robot. Their understanding of how the robot moved across the floor fluctuated along the general complexity scale, as is evident in Figure 7, varying from primitive egocentric actions that confused the robot’s characteristics with the students’ own actions to complex representational systems that specified the robot’s concrete characteristics.

Instead of a single upward trend toward a more adequate understanding, Ann and Donald’s skill was fragile, again and again collapsing and having to be rebuilt, as illustrated by the segments marked by dashed vertical lines in Figure 7. Seemingly small changes in the situation led to collapses of their skill to low levels of complexity, marked by egocentric actions that confused their own activities with properties of the robot. The collapses were followed by rebuilding their understanding again. First, a wire fell out of the robot, and they unknowingly placed it back in a different hole, producing a different response in the robot. Their skill level plummeted, and they again built up a more complex understanding over several interchanges.

Figure 7.
Microdevelopment of Understanding a Lego Robot:
Repeated Reconstruction of Skill



A dyad, Ann and Donald, worked together to understand a lego robot that changed movement in response to light. Their joint problem-solving involved repeated reconstruction, as they moved through four construction episodes in half an hour. Reference: Granott, 1994, in press

Then someone else joined them and asked what they were doing. Their verbal explanation began at a low level and was gradually built up over several minutes. Then after finishing their explanation they removed a wire from the robot and purposely placed it in a different hole, and once again their skill dropped and had to be rebuilt.

The fragility of the skill comes in large part from its lack of generalizability. Very minor changes in the situation cause the skill to fall to a low level and require reconstruction. We

suspect that this process of repeated rebuilding is an essential part of creating a generalizable skill (Yan & Fischer, 2002, in press).

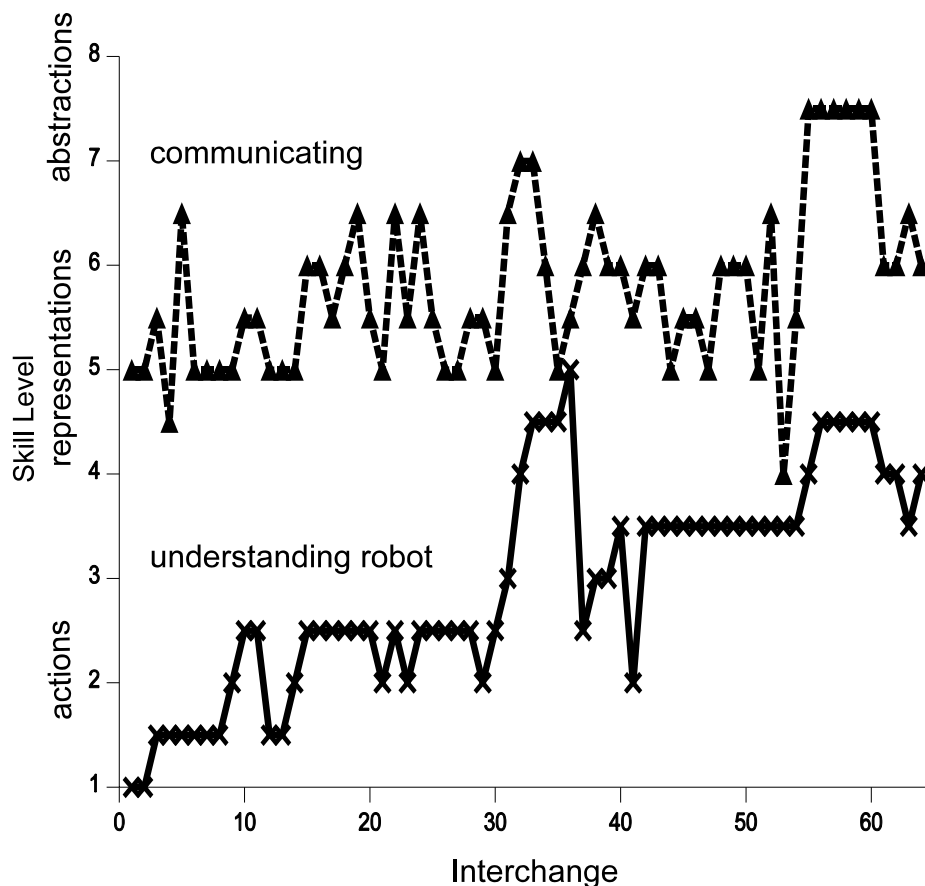
Collaborative Learning and Multiple Dimensions of Activity. Besides the nonlinear-versus-linear nature of learning, two other traditional assumptions need to be changed to take advantage of the new possibilities for analyzing learning in real-life settings, and important methodological strengths follow from the change in these assumptions. First, learners often work together more effectively than alone, contrary to psychological traditions of the individual learning alone and consistent with the social emphases of some educational research (Brown & Palincsar, 1989; Scardamalia & Bereiter, 1999; Vygotsky, 1978). Second, because people act on multiple dimensions simultaneously, their learning occurs along multiple concurrent pathways, not merely along a single linear pathway to unitary knowledge or skill. Analyzing learning as comprised of developmental functions leads beyond one-dimensional explanation of individuals' behavior and thought to multi-dimensional analysis of learning among dyads or larger groups (Fischer & Granott, 1995).

First, in studying learners as collaborators in social settings rather than as individuals who only occasionally interact or influence each other, researchers and educators both make the learning situation more ecologically valid and provide a richer source of data for analyzing learning. That is, students naturally interact socially and co-construct their knowledge as they learn unless the school situation forces them to work alone. Collaboration also makes the learning process more visible, as students communicate in ways that externalize the learning process (verbal exchanges, gestures, joint activities). Individuals working by themselves do much less externalization of learning. Collaborative learning makes visible the gropings and understandings of learners and thus creates better data for observation and study of learning. In the lego robot study, for example, Ann and Donald as well as other dyads collaborated to build knowledge by talking and interacting about the robot. In fact, the collaboration was so natural that for many dyads Granott (1994, in press) found a seamless integration of collaborative activity.

Second, growth commonly occurs along multiple concurrent strands and threads within

strands recruited for a task, some of which show learning and some of which do not (Fischer & Granott, 1995). Activity does not occur only on one dimension or at one developmental level but at different levels along different cognitive and emotional strands. In the robot study, for example, Ann and Donald showed skills for verbal communication with each other and skills for understanding the robot, and these two strands produced strikingly different patterns of growth. In contrast to the distinctive growth pattern in Figure 8 for the strand for understanding the robot, the verbal strand showed no systematic change over the course of the session. That is,

Figure 8.
Two Simultaneous Strands, One Showing Microdevelopment
and One Showing No Systematic Change



Ann and Donald developed along two simultaneous strands for understanding the robot. The strand for understanding the robot showed microdevelopment, but the strand for communicating showed no systematic growth. The graph is for the first of the four segments in Figure 7. Reference: Fischer & Granott, 1995.

the dyad maintained effective representational communication during their joint problem solving and showed no systematic growth of that communication. At the same time, their understanding of the robot (which was evident through their communication) did show systematic change, repeatedly dipping to the level of egocentric actions and growing back to more complex, representational thinking. In this way, students' learning can involve multiple, simultaneous dimensions that are genuinely distinct, not merely different aspects of measurement and analysis. In this example, Ann and Donald acted in terms of (at least) two independent strands, and only one of the strands demonstrated learning. Analyzed in terms of brain processes, we would expect the two strands in Figure 8 to be grounded in different neural networks.

Note also the differences in levels between the two strands in Figure 8. While the strand for verbal skills fluctuated between levels 5 and 7 (representations) throughout the session, the strand for understanding the robot was more variable and at much lower levels, ranging from 1 to 5. That is, students' unfamiliarity with the functioning of robots resulted in low, sensorimotor and representational levels of understanding, but at the same time their verbal skill hovered consistently in the higher levels of representations. An important ancillary point is that these students were all capable of higher levels of skill than they showed in either strand. Based on their ages and their performance in graduate courses, they were capable of using complex abstract skills at levels 8, 9, and even 10, but they did not show these levels in their activities with the robot (Yan & Fischer, 2002, in press).

Detecting the important microdevelopmental processes of construction and the nonlinear dynamic patterns of change required differentiating these two dimensions. A superficial analysis of the verbal interactions between Ann and Donald, for example, would have washed over the process of understanding the robot and showed a relatively linear, stable, flat trajectory in their relatively complex representational communication, with a few fluctuations but no learning. Generally, detecting the dynamic nature of learning in microdevelopment requires moving beyond the limitations of linear analysis of individual students on single dimensions. Indeed, the complex webs of long-term development derive from these microdevelopmental strands, which grow, join, and separate to produce nonlinear development of long-term skill and understanding.

An Opportunity: Using Technology to Study and Promote Learning. Study of the processes of learning in real time in school settings is greatly facilitated by the technological tools that have become available for schools. Students can do much of their school work on computers, and in a few school systems computers have already been programmed to provide teachers with daily information about children's performances, such as their reading and writing skills. With this information, teachers can monitor and facilitate each student's learning. In programs to restructure schools as communities of learners, computers are used to promote communication and collaborative learning and problem-solving (Brown, Ellery, & Campione, 2000; Scardamalia & Bereiter, 1999; Young et al., 1997).

These restructured settings provide the opportunity to use the computers to monitor and assess students' learning every day in real time. Researchers can use this technology to devise systems for studying learning as it occurs, analyzing it as microdevelopment. Of course, some additional tools for observation besides computers will be required for intensive data collection, but this use of computers in classrooms makes possible a new era in studying learning in schools grounded in dense data collection to assess how children actually learn from day to day.

Modeling Development and Learning

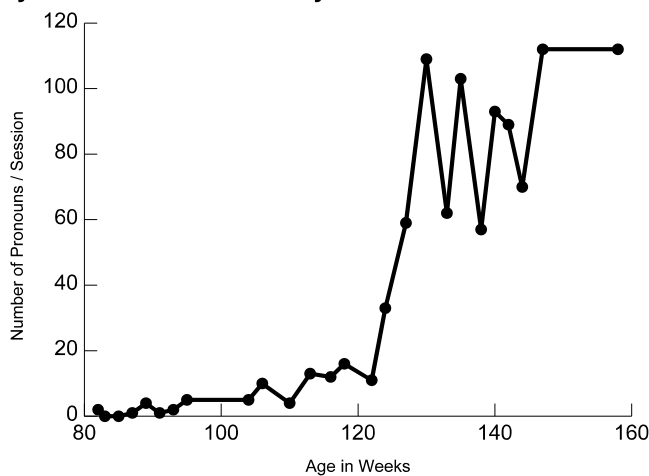
The existence of richly detailed data on performance and learning in individual students in real-life situations makes possible a new kind of analysis: modeling of development and learning. Instead of global studies that lead to vague conclusions about generic processes, educators can build specific models of the processes of learning in individuals or small groups. Powerful computer programs support nonlinear dynamic mathematical tools for modeling complex growth curves like those in Figures 1, 3, 5, 7, and 8 (van Geert, 1991, 1994). Cognitive and developmental scientists historically have posited detailed theories of how learning and development occur, and the tools of nonlinear dynamics make it straightforward to turn every such theory into an explicit mathematical model that can determine whether the theorized processes in fact produce the kind of growth patterns expected. These mathematical models can be built fairly simply with any standard spreadsheet program, such as Excel, using

difference equations similar to those used to predict mortgage interest and payments. For a description of how to use spreadsheet programs to build such models, see van Geert (1994).

As a result, educators no longer need to reduce processes of learning and development to linear forms but can analyze the complex natural growth curves that real students produce. Meteorologists now use nonlinear mathematical models to predict the behavior of individual weather systems, including hurricanes and more mundane weather, and cell biologists use them to predict the behavior of individual cells as they function and grow (Endy & Brent, 2001). In the same way, cognitive and educational scientists can use dynamic modeling methods to predict individual students' learning patterns and trajectories.

For example, explicit growth modeling makes possible research on specific patterns such as turbulence with rapid growth. A common concept about growth is that rapid change frequently leads to fluctuating, unstable behavior, such as the emotional tumult often seen in adolescents as they experience puberty or the variability in speech that is typical of toddlers developing through the vocabulary spurt at age 2, as illustrated in Figure 9 (Ruhland & van Geert, 1998). The basic form of growth in biology is logistic (log-based), and even in its simplest

Figure 9.
Rapid Development of Pronoun Use Followed by Turbulent Variability in Tomas, a Dutch Boy



Logistic growth typically produces turbulence or vacillation after rapid growth, as evidenced in the growth of use of personal pronouns by Tomas, a 2-Year-Old Dutch Boy. Reference: Ruhland & van Geert, 1998

form it turns out to produce turbulence with rapid growth: Because of its rapidity, growth overshoots the natural limit of the system (called carrying capacity), and correction of the overshoot produces turbulence like that in Figure 9. Beyond this simple logistic growth model, nonlinear dynamic tools make it possible to program sophisticated developmental models, such as Piaget's and Vygotsky's concepts of equilibration

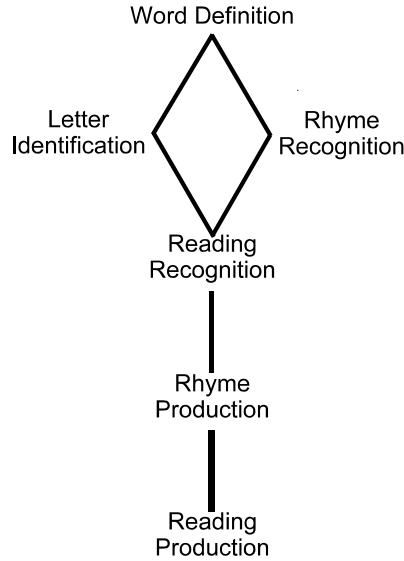
and the zone of proximal development. Van Geert (1998) showed that a nonlinear model of Piaget's and Vygotsky's concepts produced both expected growth patterns and interesting surprises, such as recurrent cycles of jumps in growth under specific conditions.

With such tools, educators can study the processes of learning and cognitive development in individual children and small groups, using models in close connection with data to investigate how learning occurs in detail, analyzing processes such as transition, generalization, and support. Initially, growth patterns observed in real learners are compared with those generated by models, and then the models are revised to better predict and analyze learning and development. This process of using models with detailed observations provides a broad new power to experiment and explore: Educational researchers can examine and manipulate the parameters of growth in particular contexts, as well as the relations between simulated skills or collaborating learners. We foresee a situation similar to those in cellular biology and meteorology, in which complex models of cellular and weather processes, respectively, are joined so closely with research on those processes that the two are inseparable (Endy & Brent, 2001). The result is powerful improvements in scientific understanding and prediction, as well as assessment. In education the practical implications for improvement of learning and teaching could make accountability of schools, teachers, and learners a potent ally of education.

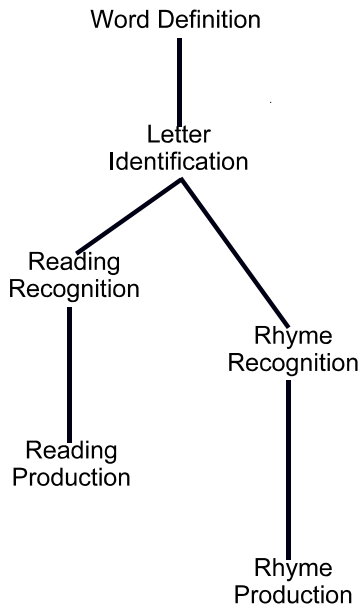
An example of how even a simple model can facilitate cognitive research is Knight and Fischer's (1992) study of learning to read single words. Analysis of reading profiles of individual children on 16 words from their reading curriculum (first, second, and third grades) showed three distinct pathways to reading. Many children demonstrated the standard, relatively linear pathway that is assumed in normative models of reading (LaBerge & Samuels, 1974; Snow, Burns, & Griffin, 1998; Torgesen et al., 1994), shown in Figure 10A. These children successfully integrated component skills of word definition, letter identification, rhyming recognition and

Figure 10.
Three Different Pathways for Early Development of Reading Single Words

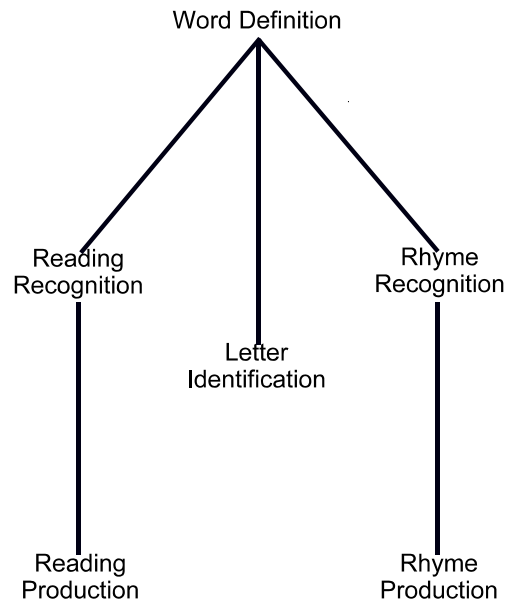
Pathway A. Normative for Reading Words



Pathway B: Independence of Reading & Rhyming



Pathway C: Independence of Reading, Letter Identification, & Rhyming



The normative pathway for reading (10A) involves the integration of meaning, visual-graphic skills, and sound analysis to create a unitary sequence of tasks. However, many children follow either of two other, distinctive pathways (10B or 10C), in which the components of reading are not effectively integrated but remain as separate strands.

Reference: Knight & Fischer, 1992

production, and reading recognition and production to form a single pathway, which was associated with reading proficiency. However, two alternative, less integrated pathways also appeared in children's reading profiles, as shown in Figures 10B and 10C, which were associated with early reading difficulties. Children developed along separate strands for reading and rhyming in Figure 10B, and a third strand for letter identification in Figure 10C, which occurred primarily in children with the most serious reading problems. With the detailed assessment providing profiles of reading skills across multiple words and tasks, the developmental pathway could be tested for each individual child. *Each child* showed one of the three pathways, with no ambiguous cases! In any domain children develop through different pathways, and educators and scientists can discover those pathways by using methods that reflect children's diverse perspectives and cultures instead of assessing only in terms of a normative pattern (Case & Edelstein, 1993; Fischer, Ayoub, et al., 1997).

Analyzing children's reading and other cognitive skills in terms of specific models of learning and development, including alternative developmental webs, will produce a powerful new kind of research tied to theory and practice, as well as powerful tools for formative evaluation. One result will be a marked improvement in teachers' ability to predict individual students' performance and to intervene to support learning effectively, using performance-based assessment and growth models to tailor lessons and assessments to particular students' needs. Importantly, these interactive and flexible tools can support students with different learning preferences and disabilities as well (Meyer & Rose, 1998).

A Fruitful Joining with Schools

Placing learning and development into a common dynamic framework grounded in cognitive science affords insights into the design of educational learning environments and the future of research on learning and cognitive development. Most broadly, it provides tools for analyzing how students act in complex social, cultural, and physical worlds that ground their activities and shape their learning. Effective teachers intuitively know that children do not construct knowledge and skill in isolation, nor do they function at a single level of unitary skill. Instead of focusing primarily on each individual and his or her static ability profile, educators

need to use cognitive science and technology to study situated collaborative learning in ecologically valid contexts, such as computerized learning and assessment environments in schools (Fischer & Bidell, 1998; Scardamalia & Bereiter, 1999; Young et al., 1997).

A key part of this dynamic framework is going beyond the endpoints of learning to analyze the variability that children show in recruiting skills to learn. Children follow diverse skill-building pathways to arrive at the “same” point. Understanding the shapes and processes of these pathways, as well as teachers’ roles in them, will make it possible to individually tailor teaching and assessments, as illustrated in the study of early reading. Putting the complexity back into learning is crucial if we are to effectively teach and assess our students.

As part of this variability, students progress and regress in dynamic, web-like pathways to learn and generalize knowledge. They do not linearly build knowledge like moving up the steps of a ladder, but repeatedly fall back to lower levels as they build up skills that can generalize across tasks and contexts. Especially when a challenging concept relies on an embedded simpler concept, students must revisit the earlier, simpler concept repeatedly to reconstruct a more complex understanding. Designing learning environments that provide opportunities for students to revisit their earlier knowledge in structured ways can facilitate automatization and generalization, allowing students to focus on different aspects or implications of the problem or solution and thus to extend their understanding to broader contexts.

In summary, microdevelopmental analysis and modeling help scientists to learn about learning and to understand the relation between learning and development. In order to understand more deeply how people build up, use, and generalize knowledge, educators and researchers must build a system that is driven simultaneously by data and theory and is both inherently developmental and adaptable for assessing over the short and long term. Combining micro- and macrodevelopmental approaches into one complexity-based, dynamic, ecological framework illuminates the structures that ground learning, and facilitates the design of curricula and teaching tools to help children learn in real-time what they will need to know over the long haul. Studying development in this way enables the construction of increasingly predictive and

comprehensive models, which as they improve, become ever more powerful tools for learning, teaching, and developmental study. Analyzing and modeling the development of specific skills in short-term, ecologically valid learning contexts can help educators to understand how learning happens and how effective knowledge building can be supported.

Conclusions: From General Structures to Contextually Grounded Dynamic Models

Discoveries from cognitive science about learning and development have both overthrown dominant assumptions of traditional cognitive science and led to new knowledge and methods that provide a strong grounding for educational research and practice:

1. Knowledge is based in constructed activity, as posited by cognitive scientists during the last century. However, the powerful, universal mental structures that Piaget, Chomsky, and others hypothesized have never been found.

2. Instead, development forms a web with parallel, independent strands/domains. What is universal is not a mental structure but the processes for cognitive development. Through a basic process of co-occurrence followed by coordination, people construct skills along a universal complexity scale in all strands of their developmental web.

3. Children (and adults) function at multiple levels of skill and understanding, even for a single topic or domain. Level of knowledge varies with contextual support, with people's concepts and skills varying across a wide range of levels, whether measured in short time intervals or long ones. Knowledge under optimal support grows in predictable developmental levels, marked by fits & starts and following a universal complexity scale.

4. The search for middle-level, domain-specific general structures has not had much success historically, with hypothesized structures for perspective-taking, metamemory, metacognition, theory of mind, and other domains all failing to show clear generalization across tasks and contexts. Overall, generalization is difficult to attain in both laboratories and classrooms, apparently because it requires long periods of repeated reconstruction. However, the long, frustrating search for middle-level, domain-specific general structures has finally met with success in Case's central conceptual structures, especially for number. These structures seem to be socially grounded in linguistic and cultural practices, which probably provide much

of the basis for their generalization.

5. The web-like nature of learning, the universal complexity scale, central conceptual structures, and microdevelopmental analysis combine with the new technological and mathematical tools of the twenty-first century to make possible a different cognitive science of education – one grounded in analysis of detailed data on learning in real-life settings such as schools. Microdevelopmental analysis of how learning occurs shows that students commonly regress to low complexity levels when faced with a new task, and then gradually build up their skill again and again, eventually constructing a skill of some generality. It is now possible to study these processes in classrooms and other real-life settings with the help of computers and other technological tools and to build explicit models of learning and development for each student or collaborating group. This new cognitive science of learning and development can radically alter the nature of educational research and provide powerful tools for improving educational practice through feedback of assessment results to classroom practices. Education can improve quickly with this kind of positive toolkit for meaningful accountability.

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