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Building general knowledge and skill: cognition and microdevelopment in science learning

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Marc Schwartz and Kurt W. Fischer

Consider what knowledge, skills or insights you might need to meet this challenge successfully: light a bulb with only *one* length of wire and a battery.[1] What do you need to know, and how do you integrate this knowledge? What role did development play in preparing you for this challenge? Science educators can identify the skills that are necessary to deal with this task. Cognitive scientists can outline the developmental progression of skills that learners build and organize to create possible solutions. In this chapter we put together cognitive development with task performance. We use a research-based practical definition for skills that allows educators and cognitive scientists to judge the complexity of activities and solutions, and to identify the processes and steps by which learners build richer understandings as they cope with challenges such as turning on the light bulb.

With these tools, we present a model of how by groping in context with a new task, people (a) construct novel skills and thus novel understanding and (b) generalize the new skills to related contexts (Fischer, Yan, and Stewart, 2003). This analysis is generally consistent with Piaget's (1952/1936; 1950/1947) emphasis on groping and adaptation as mechanisms for creation of new knowledge. It adds specific tools for describing how people use groping and adaptation to build new knowledge in specific contexts and to generalize that knowledge to other contexts. Other theories of ontogenesis have generally neglected this question and process, except in research on microdevelopment (Granott and Parziale 2002). They have typically either assumed that new knowledge can be readily created and generalized, or they have not considered the question specifically. Piaget himself did approach the question in a broad way, and the framework that we present explicates his explanation in terms of groping and adaptation (Fischer and Connell 2003).

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[1] Before continuing, you might want to spend a few minutes considering how you would proceed with this task.

Framework for analysing skills

The concept of skills shows up frequently in both cognitive development and education and is prominent in the literature on science education, science literacy, and national and state science standards. Skills are often characterized as generalized abilities such as completing electrical circuits, designing experiments, graphing data, or understanding motion and force (AAAS 1989; AAAS 2001; NRC 1996) – a framework based in the psychometric tradition and prominent in much of cognitive science (Carey 2000; Demetriou, Christou, Spanoudis and Platsidou 2002; Ferrari and Sternberg 1998; Horn and Hofer 1992). However, such a characterization has posed two specific problems for educators and cognitive scientists:

(1) The framing in terms of general abilities obfuscates the need and value of analysing these abilities in terms of their cognitive demands.[2]
(2) Generalized abilities have been notoriously difficult to teach (Case 1998; Detterman 1993; Fischer and Immordino-Yang 2002; Salomon and Perkins 1989).

Furthermore, such a conceptualization of skills makes certain questions hard to answer. How can educators determine with any confidence what has been learned? How can cognitive scientists evaluate student progress in learning general abilities such as designing experiments, graphing data, or wiring complete circuits? We will show that an analysis in terms of specific activities and skills obviates these problems and facilitates useful analysis of what students learn.

Analysis of components of skill-building

To achieve this analysis requires moving beyond a simple dichotomy of right versus wrong solutions and building instead a deeper analysis of the components or units that learners need and use in creating answers to specific tasks. Most frameworks analysing long-term changes in cognitive development (including many in this book) neglect the short-term building of components for specific tasks. A skill framework illuminates these components, highlighting the form in which students think as they try to meet the light bulb task and one other challenge – how to build a bridge (from toothpicks and marshmallows) that supports its own weight across an eleven-inch span. The framework provides tools for analysing the developmental processes in learning a task or solving a problem, a process that is called *microdevelopment* or *microgenesis* (Fischer 1980a; Granott and Parziale 2002; Schwartz and Sadler in press; Werner 1948; Yan and Fischer 2002).

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[2] Cognitive demand: the degree of coordination of more basic ideas required by a learner to construct a more complex concept.

The first goal of the chapter is to use both tasks (light bulb and bridge) to characterize student achievements within a comprehensive cognitive framework that reveals the richness and complexity of understanding as well as the evolution of that understanding. This chapter uses both tasks to explore what it means to understand and how to compare development and variation in understanding over time. Analysis of student responses exposes the units of variation and characterizes the deeper understandings that learners achieve when coordinating these units into workable solutions. This framework helps identify what is missing in any partial or developing understanding. Also, in this chapter we try to support deeper understanding in you, the reader, by creating some of the experiences that students have as they work with a task and build skill and understanding.

Skill theory, a dynamic model of cognitive development and learning, provides a framework for recognizing and quantifying changes in understanding (Fischer 1980a; Fischer and Bidell 1998). This cognitive model of human development offers two powerful tools for research: a set of procedures for defining skills and an empirically established complexity scale for assessing levels of skill construction in both learning and long-term development. Concepts of skills and levels, which are related to Piaget's (1983) original global characterization, have been refined into a set of fine-grained tools for analysis. This hierarchical model provides a framework that identifies changes and variations in understanding and can support the conceptualization of educational interventions to help students build more sophisticated understandings. In this framework, skills are cognitive structures that learners use in specific contexts and that vary in complexity, while abilities such as graphing or building complete circuits (and other such capacities that are sometimes called 'skills') will be referred to as competencies, which are made up of many related skills in our sense.

The second goal of the chapter is to demonstrate how skill analysis can capture the specific trajectories that students move through in reaching more complete understanding, often by using more complex skill levels. This type of analysis sharpens the picture of what it means to understand by identifying the levels of skills that students use and the experiences that they have to make sense of new concepts and problems. This type of analysis also highlights how new understandings are dynamic because the skill levels that individuals display are intimately associated with and dependent upon changes in context and individual state. With skill analysis, any understanding can be characterized both for its uniqueness and for its general properties, combining specification of the specific skills used and their temporal quality with their level on the general scale of skill complexity (see also Case, Okamoto, with Griffin, McKeough, Bleiker, Henderson et al. 1996; Dawson 2002; Dawson and Gabrielian 2003; Fischer and Bidell 1998; Schwartz and Sadler 2003, in press; (http://gseacademic.harvard.edu/∼hcs/base/index.shtml).

Scale for developmental analysis

Skill theory describes the changes in cognitive structures that are observed in the long term as human beings mature and in the short term as they confront new tasks (Fischer 1980; Fischer and Bidell 1998). Despite the large amount of research on cognitive development, most developmental scales have been simply used with empirical validation of their scale properties. At best, stages in other frameworks have been tested primarily for their Guttman properties (Case 1991; Dawson 2001, 2002; Dawson and Gabrielian 2003; Fischer et al. 1993; Fischer and Silvern 1985). In skill theory each level is an increasingly complex coordination and differentiation of earlier levels. Each level forms a real point on a developmental scale, because it has been documented by evidence of discontinuities with emergence of each level and evidence of strong separation of levels in Rasch scaling analysis. Also, each level seems to have specific correlates in development of brain activity (Fischer and Rose 1996). So far, research indicates that there are thirteen hierarchical levels grouped into four tiers (or stages in the terminology of Case 1991, and Piaget 1983). Ten of these are most relevant for normal cognitive development and learning in children and adolescents and are used in the analyses in this chapter; there is strong empirical support showing clusters of discontinuities at specific ages for all ten (Fischer and Bidell 1998; Fischer and Rose 1996).[3]

This framework has allowed researchers to use the same scale to identify and describe similar changes in understanding in a variety of areas (for example, Bidell and Fischer 1994; Commons et al. 1998; Dawson 2002; Fischer and Bidell 1998; Fischer, Yan, and Stewart 2003; Granott 2002; Rose and Fischer 1998; Yan and Fischer 2002). Skill analyses can reveal the range of cognitive skills used by students confronting specific tasks through descriptions of the levels of understanding they use as they solve problems. In addition, educators can use this kind of analysis to identify where interventions have affected students' specific skills and where they have not had the intended effect. The analyses provide educators and cognitive scientists insights into the patterns of activity and understanding that students demonstrate as they try to build general competencies.

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[3] In this chapter the levels are numbered as follows: The first level of the tier of sensorimotor actions is labelled Sm1 and the remaining levels in that tier are Sm2 and Sm3. The levels of the tier or representations are Rp1, Rp2, and Rp3. The levels of the tier of abstractions are Ab1, Ab2, Ab3, and Ab4, for a total of ten levels. (See Fischer and Bidell 1998, and Fischer, Yan and Stewart, 2003, for more detailed explanation.)

The patterns of activity demonstrate pathways of skill development. Each pathway involves a range of skill levels within the hierarchy of skills and depicts the underlying structures of the activities and concepts that students create. In the pathways individual students show distinct trajectories that are the outcome of the dynamic interaction of the students' activities with particular contexts. The individual trajectories are not well-marked highways that all students follow to mastery, although different trajectories may share characteristics that mark common pathways. The same type of skill structure can support misunderstandings that are just as complex as a correct understanding. Analogously, buildings may look different from the outside, but the supportive inner skeleton is still recognizable to any engineer because all buildings must withstand the same forces of nature.

In summary, skill theory provides educators and cognitive scientists the same kind of perspective that structural engineering provides architects by revealing the inner structure of understanding. This perspective is useful in not one but two important time frames. Skill levels are useful in characterizing both long-term cognitive development from birth to early adulthood and short-term learning. The developmental levels in the skill framework for long-term development can also serve as a ruler to quantify observed changes in understanding that result from learning in the short-term. The rationale of this approach is that learning is a form of short-term development – the organizing principle behind the skill analysis of microdevelopment (Fischer and Granott 1995; Granott and Parziale 2002; Yan and Fischer 2002).

Microdevelopment

Even though development through the levels observed from birth through adulthood is a process supported by maturation, people do not reach the same level of sophisticated skill and concept use in all domains – a finding that is evident throughout the literature in the widespread prevalence of unevenness or *décalage* across domains in cognitive development (Case 1991; Demetriou et al. 2002; Fischer 1980b; Flavell 1982). This phenomenon has been explored in research with children and adults confronting new problems (Bidell and Fischer 1994; Fischer and Granott 1995; Granott 2002; Parziale 2002; Yan and Fischer 2002). When learners begin the problem-solving process in a new situation, they first use primitive skills, not their most sophisticated ones. They start with less sophisticated skills in order to familiarize themselves with the problem and to start anew the process of coordinating skills into more complex, novel structures (Granott, Fischer and Parziale 2002). As they interact with the problem and gain understanding through the use of less sophisticated skills, they build a foundation specific to the problem they are working on – one that will support the construction of more sophisticated skills similar to those already developed over time in more familiar areas. Thus the process of short-term coordination mirrors the process of long-term coordination observed over years of development.

Microdevelopment is the process of recovering and reorganizing skills when confronting novel problems in order to construct new skills that are needed to meet the demands of the new problem. Microdevelopment is learning structured in the short term in ways similar to development over a lifetime (Wertsch and Stone 1978; Granott 2002).

The complexity of any problem a learner expects to solve cannot exceed the highest skill level s/he has achieved through the process of long-term development. This upper limit of performance in solving problems, called the *optimal level*, does not occur automatically in every situation a person faces, because skill performance is a function of support, context, emotional state, and practice in coordinating component skills (Fischer and Bidell 1998; Fischer, Bullock, Rotenberg and Raya 1993; Vygotsky 1978). Conditions especially conducive to eliciting optimal-level performance are high degrees of contextual support marked by priming of key task components, which offer learners conditions that facilitate new skill construction and organization.

Many researchers and educators have emphasized the role of support in the development of new skills (Lave 1993; Rogoff 1990; Vygotsky 1978), but it is often assumed that students can simply transfer ideas from one area to another. Research clearly shows that students rarely accomplish such transfer with school knowledge (Case 1998; Fischer and Immordino-Yang 2002; Griffin 1995; Nardi 1996; Pea 1993; Salomon and Perkins 1989). Support allows students to make use of familiar skills in new contexts and to function at higher developmental skills that they have not yet fully mastered. Support helps guide students toward the sophisticated understandings that science requires and that science activities without support seldom produce. A person that needs assistance to perform a skill today can gradually build toward an expert performance of that skill on her own tomorrow (Granott, Fischer, and Parziale 2002).

Development is thus a phenomenon that is observable not only as people mature but on smaller time scales of seconds to days. This short-term development, observed in learners facing new problems or familiar problems in new contexts, has been investigated in numerous studies (Granott and Parziale 2002). For example, Granott (2002) investigated the evolution of strategies that adults develop for understanding how Lego robots work. Yan and Fischer (2002) studied the learning process for adults learning to use computers to do statistical calculations. Parziale and Fischer mapped the pathways school-age students follow to learn how to build bridges with marshmallows and toothpicks (Parziale 2002; Parziale and Fischer 1998). Bidell and Fischer (1994) analysed how children deal with the tower of Hanoi problem. Schwartz (2000; Schwartz and Sadler 2003, in press) investigated how students learn to build magnets from a nail, a battery, and wire and how they understand whether objects will float or sink in water. Because skills vary along the same levels in long and short-term development, microdevelopmental analysis can capture changes in understanding in time frames that are normally encountered in classrooms and other learning environments.

Microdevelopment in action

We will explore in some detail the development of understanding in three different areas – building bridges, juggling and understanding circuits. The analysis of bridge building provides a general introduction to the skill levels that students encounter while trying to build a stronger bridge. Juggling illuminates the process of coordination of components in skills. Understanding circuits elucidates in further depth the nature of the levels that people use when confronting the bulb challenge.

Building bridges

James Parziale in his study of middle school students learning to build bridges employed skill analysis to evaluate changes as student dyads used marshmallows and toothpicks to build a bridge that could successfully span an eleven-inch gap (Parziale 2002; Parziale and Fischer 1998). Student dyads produced interactive dialogue that both revealed the skills that each student used and often supported or prompted use of more complex skills. Figure 4.1 illustrates the outcome of an interaction between two students, fifth-graders Josh and Will. Two kinds of changes were coded during 120 separate interactions between Josh and Will during one laboratory period: (1) the skill complexity evident in the dyad's activities and (2) the complexity of the bridge itself. The interactions included a variety of activities, such as testing the strength of a toothpick, connecting toothpicks and marshmallows, announcing a new observation, or posing a question.

From actions to representations

The dashed line in the graph represents the students' skill level at each recorded activity while working with the bridge components. At level Sm1: single actions, which is the simplest level in the present analysis, one student picked up a toothpick and focused on its properties ('It's warped.'). At all sensorimotor levels, the focus is on actions with the marshmallows and toothpicks, with understanding still limited to physical sensorimotor experience or action.[4] At

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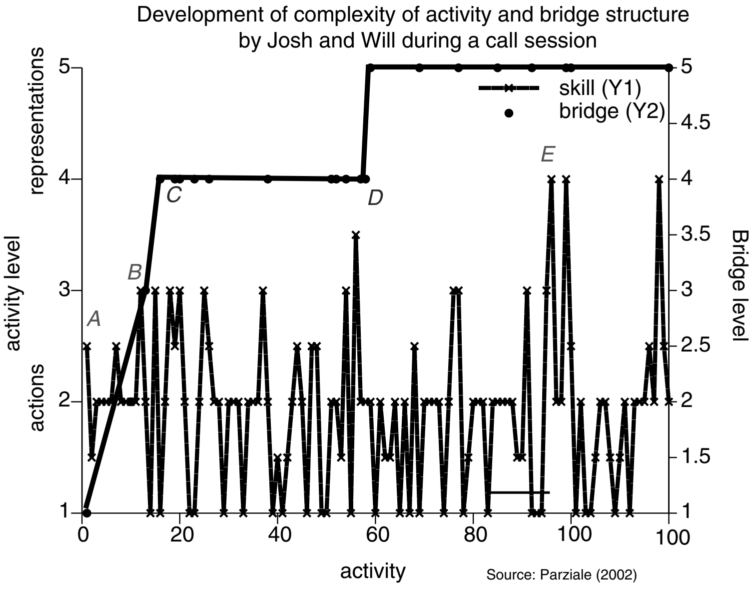
[4] Piaget claimed that such an understanding belongs to the sensorimotor stage. In skill theory this stage is referred to as the action tier.


Development of complexity of activity and bridge structure by Josh and Will during a call session

Source: Parziale (2002)

C and D mark an increase in complexity of the bridge structure. A, B, and E mark changes to new levels and other significant events in construction activities. Note the correspondence between the patterns for the most complex activities and the progress in the complexity of the bridge.

Figure 4.1. Relation of counting speed to span. (Adapted from Case 1985, 361)

Level Sm1 Josh and Will do not yet attempt to link actions with toothpicks (or marshmallows) to meet the challenge of building a bridge.

The next two levels (levels Sm2 and Sm3) involve relating actions together, such as joining toothpicks in order to make a longer section. The earlier level, Sm2, called a sensorimotor mapping, appears early in Josh and Will's activities at the start of the graph, marked A; it involves a simple relation of two actions to create a new sensorimotor understanding. Josh and Will related bridge components (connecting marshmallows and toothpicks to form a chain), because they recognized that toothpicks had to be connected to span the gap. However, the students were not yet using any guiding principle beyond a simple chain to organize the toothpicks into a bridge. At activity 15 in Figure 4.1 at the point marked B, the students began to recognize that a simple chain of toothpicks would not span the gap, because the links collapsed under the bridge's weight. They then experimented with more complex connections of toothpicks and marshmallows, building skills at level Sm3, sensorimotor systems. Thus their activities with the task supported the emergence of more complex skills.

Toward the end of the session (from interactions 96 to 120, starting at point E) Josh's and Will's work together supported the emergence of a new representation. They coordinated actions involving marshmallows and toothpicks into a new level of complexity, demonstrating a qualitatively new form of understanding (level Rp1, single representations). They had previously carried out many systems of actions that revealed the properties of the toothpicks and marshmallows by uniting the materials in various ways, and here they brought those actions together in the recognition that only certain configurations led to a stronger bridge section. They focused on a representation of one set of configurations that are strong and stable – a triangular strut.

This new skill involves a transformation from understandings based on actions to a new form of understanding involving representations that are independent of specific actions, although based upon them.[5] Will and Josh discovered the triangular strut as a special configuration by coordinating various actions while working with the material. In future conversations the students used the word 'strut' to capture the essence of this stronger configuration. They no longer needed to see or build the strut to represent its properties. They could also use words other than 'strut' to encapsulate this new discovery, with any representation they used serving the same purpose – capturing the actual configuration of this stronger bridge section.

The new form of understanding that emerged at level Rp1 also coincides with an improvement in the bridge structure – the triangular struts are now included in the bridge to help distribute the weight of the bridge components. Using the same complexity scale, we can compare the changes in skill level at each activity to the complexity of the bridge that each dyad built during the same interval (the solid line). The graph illustrates how the skill structures that appear in the student's interactions can be related directly to changes in the bridge. The activities only involved building parts of the bridge, and so they typically remained less complex than the bridge itself; but the most complex activities match advances in building a more effective bridge (points C and D in Figure 4.1), which reflects an increased complexity in design not observed earlier.

The association between skill development and bridge complexity provides a start for understanding the relation between student ideas and the scientific concepts behind bridge building. This relation does not proceed far without contextual support, however, because achieving higher-order skills in science is not easy to do alone or even in peer groups (Bredderman 1983; Schwartz 2000). Student ideas in science are often not only different from a scientist's understanding, but resistant to influence from teachers and curricula (Driver,

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[5] Piaget first identified this kind of understanding as belonging to the early pre-operational stage. In skill theory this level begins the representational tier.

Guesne and Tiberghien 1985; Driver, Squires, Rushworth and Wood-Robinson 1994; Shamos 1995).

Developmental range

Student concepts and activities involve variable, not permanent structures, demonstrating a range of skill complexity that varies with support and other factors. This flexibility in performance occurs within the learner's *developmental range*, which describes an array of skills at various complexity levels, as reflected in the ups and downs of activities in Figure 4.1. At the lower end of the range, learners are typically solving problems alone or in low-support environments and are thus operating at or below what we call a *functional level*, the best that they can do without support. When learners act in highly supported or scaffolded contexts, they can perform at their optimal level, the highest level that they are capable of. For Josh and Will their optimal levels were level Rp3 representational systems or level Ab1 single abstractions, depending on the domain. In the bridge-building activities in Figure 4.1, they never reached their *optimal level*.

An individual's developmental range – the interval between their functional and optimal levels, between the best that they can do without and with contextual support – changes with development. Using the skill hierarchy, researchers and educators can describe the specific range of variations that a person shows in learning a skill and the pattern through which they grow their skill. Different individuals in different tasks will produce diverse growth patterns, and also two skills of the same complexity can have diverse content.

Cycle of levels in tiers

Understanding within the action tier for the task of building a bridge begins with individual actions using toothpicks and marshmallows. For example, learners explored the materials (e.g. Do toothpicks bend easily? In which direction do they best withstand attempts at compression?). They next discovered ways in which action understandings about toothpicks might or might not extend to the marshmallows. Success in coordinating multiple actions ultimately supported the emergence of a new tier of understanding, a new kind of skill called a representation.

The same general strategy of coordination repeats in parallel fashion in the representational tier through the integration of earlier levels into later levels. The four levels of representations are single representations,[6] mappings of representations, systems of representations and coordinations of systems into single abstractions. Each tier shares the same general pattern of coordination, as

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[6] Note that in the bridge example, single representations were identified only as a level Rp1 skill or understanding.

shown by the names of the levels – for the action tier, single actions, mappings of actions, systems of actions, and coordinations of systems into single representations (Fischer 1980b; Fischer and Rose 1996). This pattern also appears in the final developmental tier of abstractions: single abstractions, mappings of abstractions, systems of abstractions, and coordinations of systems into principles.

To illuminate the nature of coordination that unfolds in any tier we use a juggling heuristic. Learners are coordinating skills within their developmental range in the same fashion that jugglers learn to keep more and more balls coordinated. The juggling heuristic highlights the strategy of skill development as learners coordinate skills at earlier levels into more complex skills at later levels.

Juggling skills – a heuristic

In learning how to juggle, training books recommend that learners begin with one ball and learn how to pass this ball back and forth skilfully from one hand to the other (Ashman 2000). This technique allows the learner to focus on the ball, the movements their arm makes, and the trajectory of the ball as it leaves the hand. This accomplishment may not look like juggling, but it serves as a foundation for juggling. At the next level, the juggler adds an additional ball to the task. The juggler will now pass the ball from each hand to the other hand. This activity still does not look like juggling, but this new level of coordination is necessary before a third ball can be successfully added. This technique of building towards increasing levels of coordination is analogous to the coordination of single representations into first mappings, and then mappings into systems of representations.

The nature of building new skills can thus be seen as two operations. The first operation is strategic in that increased competency is demonstrated by keeping more balls or representations coordinated. The second operation is tactical in that the juggler must choose different items to juggle: balls, knives or torches present different challenges. The difference in objects is analogous to the difference in ideas and activities found in various disciplines that are coordinated into more complex understandings. This strategy of increased coordination is what we will explore in more detail as learners respond to another task, lighting an electric bulb, by discovering ways of coordinating representations into increasingly more complex solutions.

The juggling heuristic offers three other insights about skills and skill development besides the strategic/tactical distinction. First, juggling has a temporal quality that suggests that new or developing skills can only be observed once the balls (knives or torches) have been set in motion. The immediacy of juggling nicely illustrates the learner's dynamic enterprise of building more complex activities. Support and practice play vital roles in the stability and variability of any new activity. New skills exist as a fragile temporal-spatial relation of components like the juggler coordinating and keeping in motion additional balls. New understandings show the same lack of stability that jugglers face when attempting to coordinate an additional ball in a routine that they have already learned to handle.

The second insight is how juggling is context-dependent. A juggler may be able to juggle three balls, but that does not mean that s/he can juggle three knives. Being able to juggle three balls also does not mean that the juggler can juggle three balls while balancing on one foot at the top of a stepladder. A skill is not just the description of a behaviour. A skill is the display of a specific behaviour in a particular context. Skill levels change as contexts change. Knowledge varies powerfully across contexts – even contexts in which the 'same' skill could be used.

Third, the nature of juggling changes as learners develop more stable higher order skills. In juggling balls, the initial assumption was that each ball was a stable structure symbolizing a single representation. When a juggler is dealing with moving one ball in his hand, mapping two balls in motion together is enormously challenging. As the juggler develops a skill of mapping two balls to each other, the mapping itself can become a stable structure. To coordinate a mapping, the learner unites the two balls into a larger, more complex structure that becomes a single, stable unit of its own. At this level of competence the learner begins passing the mapping from hand to hand before other mappings and/or single representations are added to the juggling act to meet the demands of more complex tasks, where the necessary or required understanding is a more complex structure (such as a system of representations).

Learning to juggle skills is not an easy task, yet nature endows people with the ability to juggle from birth. As the nature and number of items being juggled changes, new skills and skill levels emerge. The same juggling operation helps learners reach greater complexity in each tier.[7] Each new tier offers learners a qualitatively new way of understanding their world that encapsulates earlier understandings, and the coordination of more complex skills in the new tier proceeds in the same way.

In the next section we elaborate both the transition between tiers and the emergence of new skills, exploring the differences in skill level and their implications for learners working towards an effective solution. The observation that

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[7] There are four documented tiers: reflex, action, representation and abstraction. More information about the reflex tier can be found in Fischer (1980b) and Fischer and Hogan (1989). The reflex tier is not introduced in this chapter because it is observed only in infants during their first months of life. Reflexes are ultimately coordinated into single actions, which is the first time infants control a movement relatively independently of postural constraints (such as reaching for a ball or following a ball with their eyes).

there are alternative pathways that can lead to an ideal solution reinforces the idea that there is not one linear series of steps that all learners take to achieve an expert understanding. Student understandings can reflect different uses of the same skills, which lead them to different conclusions about the natural world.

Building electrical circuits

The prevalence of diverse solutions to tasks such as the light bulb problem was first illustrated in the documentary *Minds of our own* (1997). The film highlights the variety of beliefs new graduates and scholars at a leading American university hold about electricity and circuits, many of them wrong in a strict technical sense. For the purposes of this chapter, the solutions suggested by those interviewed in *Minds of our own* as well as many other responses from student interviews show a range of understandings that when unpacked provide a richly textured view of the nature of understanding, the relation between alternative solutions, and the microdevelopmental progression of creating a novel understanding.

Each solution or strategy that a student uses represents different choices about how to coordinate beliefs about the world with specific content encountered in and out of school. Science educators have often focused on the *misconceptions* implied by unworkable strategies, claiming that they impede understanding. Evidence of misconceptions or naive conceptions are well documented in science education (Driver et al. 1985, 1994; Novak 1987), but we argue that these misunderstandings are better understood as alternative pathways of understanding, often based in a schema or metaphor that frames a range of skills and can lead to better understanding. (Schemas are to be distinguished from what Piaget (1983) calls ‘schemes’, which are the general structures for acting and knowing that each person uses.) Students grope with tasks by means of these schemas, and through the groping they can create an understanding that is novel for them. The diverse pathways provide important information for scientists and educators to develop insight into how learners coordinate skills to form more powerful understandings.

The initial solutions offered by three adults attempting the light bulb task provide a way to explore how skills evolve in complexity (Figure 4.2). The three drawings may also summarize or highlight achievements you have made in understanding circuits. For example, you should have little difficulty recognizing the wire in each solution.

If you recognized the wire, you might ask yourself, ‘How did I do that?’ The wire’s appearance is different in each case. To recognize the wire in each drawing requires a more fundamental understanding embedded in an earlier form of understanding – sensorimotor or action understanding. You know from prior experiences that wire is easy to bend, that it can maintain different shapes,

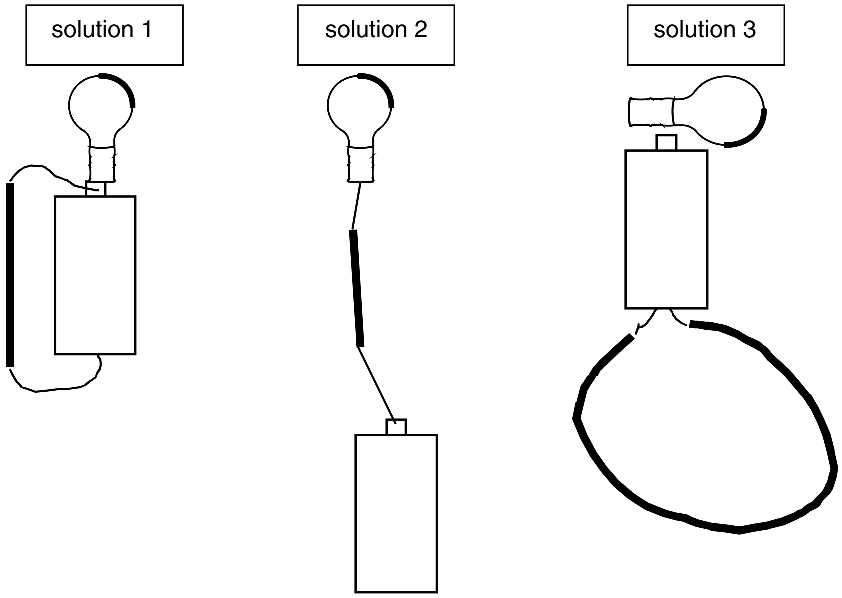
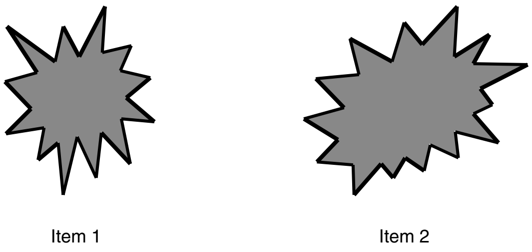


Figure 4.2. Three attempted solutions to lighting a bulb with one piece of wire and a battery.

that there is often a covering on the wire that can be brightly coloured or not, and that under the cover is a shiny metallic core. All of these observations and experiences with wire are key levels of action understanding embedded and already coordinated in the first tier of skill development. However, as adults we have lost touch with the work involved in creating symbolic understandings from our actions, and as a result we no longer recognize or appreciate the importance of this transition.

Transitioning from actions to representations

The transition from action understanding to representational understanding is a powerful experience. Before considering further the representations unique to circuits, we want to explore the nature of the transition from level Sm3, the last level of the action tier, to level Rp1, the first level of the representational tier. This transition is just as powerful as the transition from representations to abstractions or from abstractions to principles, but it can be harder to illustrate. To experience the impact of the transition from actions to representations and the new world that unfolds as we coordinate these representations into ever



Item 1 Item 2

Figure 4.3. Blurbs.

more complex structures, we will examine a representation that you do not yet recognize (Figure 4.3).

Item 1 in Figure 4.3 is a ‘blurb’. You don’t know what blurbs are yet, but after looking at the first blurb, you will probably suspect that Item 2 in Figure 4.3 is also a ‘blurb’. Why? This ability to recognize similar objects and to recognize these objects by name is a conspicuous skill in toddlers because single representational skills mark the leading edge of what they are learning to accomplish on their own (Corrigan 1983; Fischer and Corrigan 1981). Toddlers name objects without knowing what they are or the purpose they serve. You are experiencing the same effect with blurbs. However, for you in contrast to a toddler, the time spent at this first level of the representational tier will be relatively short-lived. Pay attention to your experience as we add the following information about ‘blurbs’: The blurbs in Figure 4.3 have been magnified 100 times, and blurbs are always found at the end of sentences.

At this point you may recognize that the authors are talking about ‘periods’. The moment that blurbs become periods, literate individuals can quickly coordinate other related representations with this single representation. For example, writers do not use blurbs (periods) after questions, and probably do not use them after bullets in lists. Three periods in a row means something different from one period at the end of a sentence. Readers expect only one period after a sentence like this one. Being able to distinguish blurbs in a world full of non-blurbs is a level of understanding characterized by the first level of the representational tier. Recognizing the relations of blurbs to other entities is an indication of the coordination entailed when operating at later levels in the tier.

An important point about single representations is their ability to persist as characteristics specific to objects that vary along some dimensions. For example, size, shape and shading are characteristics of blurbs. If you encounter a blurb-like object that is twice as big as Item 1 or 2, or has only two or three points, or has the outline of a blurb but is white inside, is this new object still a blurb? There is a range along which each characteristic can be amplified or dampened without inadvertently creating a new object or new representation. It is difficult to say where the limits are for each person, but they frame the boundaries that allow people to recognize objects that belong to the same group. When the acceptable range for blurbs has been exceeded, then people are no longer sure whether the new object is a blurb or not.

Single representations act as foundational skills that serve as the platform for building more complex representations. Each successive level for understanding the light bulb task is organized and coordinated into increasingly more complex cognitive structures. The levels of understanding that students and adults reach with the light bulb task reside mostly in the representational tier. The levels of understanding within this tier are typically sufficient for handling many of the problems we encounter in life, with no need for abstractions (Fischer, Yan and Stewart 2003; Yan and Fischer 2002).

Level Rp1: single representations in circuits

A second question about the three solutions in Figure 4.2 will help introduce another single representation necessary to understand circuits. Which object is the battery? Recognizing batteries, like the wire, requires a rich tactile and visual range of coordinated actions. Batteries are hard; the ends are shiny. One end has a little bump. The other end often has a dimple. There are a number of continua along which batteries might change that can eventually disrupt the pattern of actions necessary to separate batteries from non-batteries.

Young children easily demonstrate the limits of this skill as they are learning to master single representations. In one pilot study of seven three-year-olds, the children easily identified AAA, A, and D batteries as all batteries even though they differed in size. Varying the size of the batteries in this way did not change the representation for these children, but the range of the size dimension can be exceeded. When these children, all becoming proficient at many skills at level Rp1 (single representations), were shown a lithium watch battery, the battery[8] representation broke down. Most asked, ‘What is it?’ Some claimed it might be money or even the tip of a bigger battery. When the interviewer (Marc Schwartz) asked whether the object could be a battery, most of the children said that it was too small to be a battery, or they asked, ‘Where does it go?’ – where does it fit on a battery.

Experience easily expands the range of a dimension. One boy, Jimmy was not confused by the watch battery; his father was the maintenance man at the preschool where the pilot study was conducted. He looked at the AAA battery

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[8] You might take a few moments to consider why you are not confused. What skills have you coordinated that allow you to include lithium watch batteries in the group of objects called batteries?

and did not hesitate, 'That's a "Duracell".' When shown the watch battery, he immediately explained, 'That's a button battery, and it has acid inside. Acid makes the battery work.'

The difference in performance between Jimmy and his playmates can be reproduced in adults by altering the context in which they have become accustomed to seeing a battery. If you saw the drawing of the battery (as drawn in Figure 4.2) on a yellow diamond road sign, would you recognize the battery, or would you see something else? In this context, your challenge is to create a single representation, which most likely begins with the question, 'What am I looking at?'

Even though young children and adults are developmentally prepared to handle single representations, the skill is not a fixed structure guaranteed to surface when needed. Changing the context or changing one or more characteristics beyond an acceptable range can degrade or interfere with the single representational skill so that understanding requires that the individual move to a lower level skill to become reacquainted with the object through sensorimotor actions.

Level Rp2: Mappings of representations in circuits

With the juggling heuristic, the comfort in handling single representations is like the ability to handle one ball skilfully in the hand. What would it mean to handle or juggle two balls? An understanding at the second level of the representational tier requires that individuals coordinate an additional dimension to relate two different characteristics that vary along relevant dimensions. Individuals discover the relation of both characteristics to the initial representation, which leads to a meaningful new understanding about the representation. At level Rp1, learners could vary the size of the battery considerably without being confused about whether it was still a battery. For example, when asked why some batteries were bigger than others, Juliette (from the toddler pilot study) pointed to the D battery and explained, 'That's a Papa battery' and continued, pointing to the AAA battery, 'That's a baby battery'. Most of her classmates responded to this question in a similar fashion by repeating back salient characteristics about its size – the bigger battery is taller or the smaller battery is skinnier.

However, these same children had difficulty coordinating related information about batteries. When I asked Juliette what batteries are for, she told me a story about how her doll needs batteries to talk. She knows that batteries are necessary to make the doll talk, but this knowledge acts as a separate uncoordinated single representation about dolls. Talking dolls need batteries. Or as Jimmy will say with confidence, the battery has acid in it, and flashlights need them. But neither child can yet create a mapping of representations about batteries, such as explaining why batteries come in different sizes or what is changing in batteries as they get bigger or smaller.

Around 3.5 to 4.5 years children begin to create a new kind of skill across many contexts, coordinating an additional dimension to form level Rp2 mapping of representations. The additional dimension about batteries that most children, adolescents, and adults in well-developed countries recognize is that they are a source of electricity[9] for toys and tools. Thus a new dimension in which batteries can vary is the amount of electricity they provide. One possible way to vary the amount of electricity the battery provides is to vary the size of the battery. Coordinating variations along both the dimensions of size and amount of electricity in the battery changes the understanding about the representation in consideration. A big battery provides lots of electricity. A small battery provides less electricity. Juliette knows for example that her talking doll needs batteries to work, but at age three she did not yet coordinate battery size with amount of electricity. Being able to coordinate both variables would be an indication of the emerge level Rp2.

When children coordinate both dimensions, they can seek to improve the function of an electrical device by asking for a bigger battery (Schwartz 1998). They may claim that a bigger battery is more powerful. Even if the size to power relation is not technically correct, this view is coherent with one popular hypothesis, schema, or metaphor about the world: bigger is better (Lakoff and Johnson 1980). The metaphor 'bigger is better' is a powerful reminder of one of the mapping relations that people observe in many situations in life.

Schemas, metaphors, or central conceptual structures provide general frameworks or shells that conveniently capture relations or dimensions about the world and form frameworks for many skills (Case 1991; Fischer and Immordino-Yang 2002; Granott et al. 2002; Lakoff 1987; Perkins 1997). Many schemas help people organize understanding at the mapping and higher levels. For example, the number line serves as a general structure that grounds many different activities involving the use of number (Case et al. 1996). These structures organize causal relations that people have discovered in the world and thus are useful in shaping the predictions people make about how the world works.

A schema that shapes understanding electricity is the source metaphor, which specifies three components: a source, a delivery mechanism, and a user at the other end. Students typically rely on their experience with plumbing to organize all three components: a reservoir serves as the source, the pipes become the delivery mechanism, and the consumer waits at the faucet. Ten and eleven-year-olds will explain that electricity flows through the wire to the bulb like water flowing through a pipe (Shipstone 1985; Schwartz 1998).

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[9] Children and adults also use alternatively the following terms: energy, stuff, or power.

The source metaphor seems to lead to a way of coordinating knowledge about the battery and the wire – battery as providing power and wire as serving as a path. From the perspective of juggling, the source metaphor helps establish and stabilize relations between these ideas, resulting in a richer understanding of circuits. With the metaphor students can consolidate several dimensions, and instead of juggling two separate balls, they can handle both balls as one larger, more complex structure bonding the balls together. The first ball symbolizes the battery and one salient characteristic – the electricity it provides. The second ball symbolizes the wire and its special property as a path. There are a number of different types of paths that are possible (e.g. one-way, two-way, narrow, etc.), but the plumbing metaphor draws the learner's attention to the one-way path required by the source metaphor. The learner as juggler is thus focusing on one variation in each representation. In the resulting mapping, the source of energy and the path are coordinated into an understanding about circuits (that the battery is a source and the wire is a one-way path.)

Children and adults using solution 2 in Figure 4.2 demonstrate this form of mapping. They explain that the wire acts as a pipe to get electricity from the battery to the bulb. Relevant dimensions highlighted by the source metaphor are 'source versus non-source' and 'one-way path versus alternative paths'. Each single representation within a mapping can hypothetically embody a variety of characteristics that vary along independent dimensions, but in an active skill at the mapping level, only one dimension is under consideration for each representation.

In general, proposed solutions at the mapping level do not suffice to actually light the bulb. Building additional mappings will not create a solution either, but they can lay the groundwork for a solution constructed at the next skill level. For example, some learners point out that batteries are a source of energy and that all batteries have two sides that are different. Although this mapping alone is not useful as a solution to the light bulb task, it will play a role in more complex solutions. New mappings and dimensions of the representations need to be coordinated to create a successful solution. This increased level of coordination is embodied in solution 1 in Figure 4.1 and in the descriptions learners used to justify that solution.

Level Rp3: a system of representations

Solution 1 is a less common alternative, and although incorrect, it nevertheless illustrates a more complex, sophisticated skill. Student explanations for this solution reveal a new coordination of two mappings. This new skill level generates a novel view about batteries. Some students explain that the battery must be activated or charged before it will work, and so they use the wire to connect both ends of the battery. Charged batteries are on (empowering the battery to deliver energy) and uncharged batteries are off (and thus the battery cannot deliver energy). The second mapping used in this new skill level is an outgrowth of the plumbing idea from the source metaphor: the wire is used to turn the battery on by making electricity flow. Students using this skill place the bulb on top of the battery, explaining that they don't really need the wire to connect the bulb to the battery. Essentially the shortest path from the source to the bulb is to simply lay the bulb on the battery – which will not light the bulb, in fact.

This new skill, which coordinates two mappings at the same time, illustrates the third level of representational thinking – level Rp3, a representational system. A new mapping concerning batteries is being coordinated with the earlier source metaphor/mapping. In terms of juggling, the student has put in play together two mapping skills: a new representational mapping for batteries coordinated with a mapping for simplified circuits captured by the plumbing metaphor.

Students who use this particular system, as embodied in their explanation of solution 1, quickly discover that the bulb does not light. Thus they quickly see that this representational system is not reliable. For the student there are a number of possible problems: one of the dimensions within the system of mappings is not relevant, or another more promising dimension in one of the mappings has not been considered, or the two mappings chosen for coordination are not appropriate. When a student makes any of the changes implied by these problems, s/he has to coordinate new mappings to create a new system skill.

When students fail to light the bulb, they are forced to examine the reliability of the system they are attempting to coordinate. The potential problem with this system creates an opportunity to challenge both the importance of the mappings and its dimensions as well as to consider investigating new dimensions in one or both mappings. One student explained that she felt certain that there needed to be a source that delivers electricity to the bulb. Thus the source metaphor or mapping remained intact, which allowed the student to shift her attention to the 'charged battery' mapping, and to think about the 'charged versus not charged dimension' that she was holding (and attempting to juggle) concerning batteries. Even though she explained that she had never seen such an arrangement with batteries and wires, she still needed to see if the battery needed to be 'charged' before abandoning this mapping – trying out the arrangement in action. Note the important role that understanding at the action tier plays in supporting skill development (such as seeing that the light does not turn on). After this student made this observation, she felt free to discard the incorrect mapping.

A new and relevant dimension about batteries surfaces when students attend to the fact that there are two sides of the battery, and that each side is different. Students who discover that solution 1 does not work become more sensitive to the two sides of batteries (which is not to say that students have to pass through solution 1 in order appreciate that both ends of the battery are different). Some students claim that any solution requires that both ends of the battery be used (although they may not be sure why). Some may point out that one side is positive and the other is negative without being able to explain what makes one side positive or negative. The new mapping provides an altered focus, which is powerful enough to change the way students attempt to light the bulb.

With this new focus, some students for the first time talked about whether the circuit was complete or not. The dimension of complete vs. incomplete circuits is a new and important concept, which begins to take shape in a strategy such as 'solution 3'. Note that in solution 3 the wire forms a circle to illustrate 'completeness' by joining both ends of the wire at one of the ends of battery. However a complete circuit must coordinate several dimensions about the battery – both making the wire close the circuit and including both sides of the battery. Even though students were still not sure how to coordinate these dimensions with the materials at hand, they quickly abandoned solution 3 not only because the strategy failed to light the bulb, but also because the solution failed to use both ends of the battery even though the circuit looked complete. The key to lighting the bulb is to coordinate the correct two dimensions in the circuit mapping.

Students working with the materials began talking about the bulb in terms of two contact points instead of one. They examined the bulb more closely, sometimes questioning whether there are two sides of a bulb, and if the position of the bulb on the battery matters. Students sometimes experimented with this new dimension as a variation of solution 2 in Figure 4.2. Instead of putting the wire to the end of the bulb, they attached the wire to the side of the bulb. When asked to predict what would happen, students often admitted that they did not think this strategy would work, but they felt strongly that they needed to test the dimension before they could move beyond it.

You may have noted that this testing phenomenon is the second example of students building a design that they did not believe would work. Why would anyone do this? One explanation comes from the microdevelopmental perspective. Students need to build representations based on their own sensorimotor understandings. The advantage of testing the design is that the sensorimotor outcome provides direct information, not information coming from an outside authority (such as a teacher or book). Once students have created their own sensorimotor understanding, they are usually ready to accept the resulting representations as their own. This is an important point for educators who believe that representational knowledge can be transferred to students by simply telling it to them – a process that forces them to 'borrow' representations instead of 'building' their own (Schwartz and Sadler 2003, in press).

Exploring whether the side of the bulb is different from the end of the bulb is sometimes productive because some students experiment with one contact point versus two contact points. At this point students used either the side or the end of the bulb as one of the contact points for the battery, which leaves the other side of the battery and the unused contact point on the bulb as the contact points to be connected by the wire. With this new configuration, the bulb for the first time will light. (If you have not worked with circuits, you may have to make an effort to juggle the representations together to understand this solution.)

The skill for this working solution is at the same skill level as the earlier incorrect solution (number 1 in Figure 4.2) because only two mappings need to be coordinated in order to light the bulb: Bulbs and batteries have two active sites (or contact points), and the path has to connect all the sites. The one-site versus two-site dimension can also be framed as ‘incomplete versus complete circuits’, and the dimension of ‘one-way path versus some alternative path’ can be framed as ‘flow versus non-flow’. This new coordination is initially tenuous in most students. Its fragility is evident, for example, when a teacher asks a student whether it matters which side of the battery is connected to the bulb. In practice, this new question can be resolved quickly by reversing the battery to find out that the side doesn’t matter, but students usually grope and stumble to construct that understanding.

Being able to coordinate two mappings at the same time is the template for a representational system. In Figure 4.2, solutions 1 and 3 reflect different mappings coordinated into a level Rp3 representational system. This fact may not be intuitively obvious, but the skill analysis of each student’s explanation indicates the similarity in these apparently different solutions. For students to make the transition to the next level, single abstractions, they need to coordinate several such representational systems to create the new kind of skill.

Level Ab1: systems of systems of representations, which are single abstractions

Although the dimension of two poles versus one pole (negative versus positive sides of batteries) was not needed to solve the original problem, polarity becomes one more necessary dimension about batteries that students must coordinate to move to the next level of understanding – systems of systems of representations, which are single abstractions. As learners coordinate multiple representational systems, a new and qualitatively new form of understanding emerges – abstract thinking. The number of representational systems that need to be coordinated to develop an abstract understanding about circuits is not fixed. In the simplest case, two coordinated representational systems (including the dimension of polarity) may be sufficient for an emerging abstraction. The coordination of multiple systems leads to a richer abstract concept of circuit.

Table 4.1. *Dimensions along which representations about the bulb task may vary.*

Objects Represented	Bulb	Wire	Battery
Dimensions	– State of the bulb: on vs. off. – Contact points: one versus two. – Incomplete vs. complete circuit: Both contact points must be part of the circuit.	– Path vs. non-path: The path must establish a route for electricity. A string could not provide this function. – Incomplete for complete circuit.	– Source vs. non source – Charged vs. not charged – Two sides of the battery: Each side must be part of the path. – Batteries have two poles.

An abstraction about circuits coordinates the multiple dimensions of the initial three single representations (batteries, wires, bulb) into an intangible, generalized concept of circuit. The essential feature of abstractions in the new tier is that circuits are understood through concepts that go beyond the concrete particulars, so that representations no longer need to be the immediate focus. Ultimately abstractions about circuits need to coordinate a number of dimensions about batteries, wires, and bulbs. Table 4.1 summarizes the several dimensions that abstractions can coordinate to form a broad concept of circuit.

Educational implications

Even though cognitive development, practice and scaffolding support increasingly more sophisticated skills as students gain experience and maturity, there is no guarantee that they will recognize and effectively coordinate the representations that are afforded by the worlds of school and the rest of life. Learning is a process where people make use of their developmental history to build the skills necessary to face new problems in a manner that is similar to the development of skills from infancy to adolescence. Learning is a constructive process in which a person must juggle and coordinate several events or characteristics concurrently to create a new skill. Students have the potential to address new problems by using their maturing cognitive capacities to build new skills, and this process is always fundamentally affected by context. Support and scaffolding play important roles in facilitating microdevelopment (learning) as students have opportunities to perform at their optimal levels, and thus to take advantage of their most sophisticated skills.

A powerful and compelling tool that students use to organize skills is schemas, metaphors or central conceptual structures. Schemas are an important platform for students in that they support the organization of actions and concepts in particular forms. Languages and cultural practices embody schemas, metaphors and central conceptual structures, and consequently children live in the presence of many structures that can support their learning and understanding (Case 1991; Fischer and Immordino-Yang 2002; Granott et al. 2002; Lakoff 1987; Perkins 1997). Schemas serve as first approximations about how nature works by focusing attention on a limited number of dimensions. While schemas thus offer insight, they also constrain more widely coordinated views about the world. When students have the opportunity to use their schemas to address tasks or problems such as the bulb and bridge-building tasks, they are challenging their view of the world.

Teachers and class activities must address the schemas and metaphors (and 'misconceptions') students use by inviting them first to recognize the structures they are using, and then to challenge these structures in new contexts. For example, students who use plumbing as a source metaphor explain that the electricity flows through the wire, but when a teacher points out that the wire is solid, students have the opportunity to reconsider the limits of the metaphor.

Identifying the cognitive structures students use in addressing key tasks is an important platform for educators. Recognizing these structures helps educators understand the range of understandings used in a population of students, and also highlights the skills that need to be supported to help students reach new levels of competence in science (Demetriou et al. 2002; Fischer and Immordino-Yang 2002; Griffin and Case 1997)

Conclusion: creating new understandings

In this chapter we aimed to show how people construct new understandings by tracing the cognitive structures that students use when trying to solve two kinds of science problems. We used skill theory, a neo-Piagetian framework, to trace the trajectory of understanding from sensorimotor through representational and on to abstract skills that students coordinated in order to understand the solutions they created to solve the bridge and light-bulb tasks.

Students used sensorimotor actions to build up single representations about batteries, wires and bulbs (or marshmallows, toothpicks and bridges), but in terms of the task of lighting a bulb, the representations alone did not empower students to do anything more than recognize a few similar features in the objects. By acting on the objects and exploring them, students built on their representations and uncovered a number of dimensions that added depth to the representations; and some of the dimensions turn out to be relevant to solving the task. In single representations, students handle one dimension at a time, focusing on one variable aspect of the object or representation, which has important similarities to juggling one ball. Coordinating two representations that each vary along one dimension in a representational mapping is similar to juggling two balls.

Schemas or metaphors such as the source metaphor can help stabilize this mapping coordination and direct thinking and learning (leading to both misconceptions and conceptual advance). Schemas and metaphors capture some aspect of the world that people have experienced in multiple contexts, and they are typically embodied in language and cultural practice.

Students coordinate mappings to create representational systems, like juggling four or more balls. A representational system is necessary to solve and explain the light-bulb task, but representational systems can also generate incorrect answers. To intervene effectively to facilitate student learning, educators need to know the dimensions that students must attend to in order to learn, as well as the other dimensions that students typically use, especially those that they favor. However, solutions that do not work are not simply incorrect. They provide clues into how students are thinking and how curricula might challenge their alternative solutions – information to help students build microdevelopmental pathways to better knowledge. Skill theory provides the cognitive framework to analyse the microdevelopmental processes through which students use skill structures to construct new understandings and generalize them to solve problems, both in school and in their daily lives.

REFERENCES

AAAS (1989). *Project 2061: Science for all Americans*. Washington DC: American Association for the Advancement of Science.

(1993). *Benchmarks for science literacy*. Washington DC: American Association for the Advancement of Science and National Science Teachers Association.

AAAS and NSTA (2001). *Atlas of science literacy*. Washington DC: American Association for the Advancement of Science and National Science Teachers Association.

Ashman, S. (2000). *Juggling – all you need to know to develop amazing juggling skills*. Bath, UK: Paragon.

Bidell, T. R. and Fischer, K. W. (1994). Developmental transitions in children's early online planning. In M. M. Haith, J. B. Benson, R. J. R. Jr., and B. F. Pennington (eds.) *The development of future-oriented processes* (pp. 141–76). Chicago: University of Chicago Press.

Bredderman, T. (1983). Effects of activity-based elementary science on student outcomes. *Review of Educational Research*, *53*, 499–518.

Carey, S. (2000). Science education as conceptual change. *Journal of Applied Developmental Psychology*, *21*, 13–19.

Case, R. (1991). *The mind's staircase: exploring the conceptual underpinnings of children's thought and knowledge*. Hillsdale: Erlbaum.

(1998). The development of conceptual structures. In D. Kuhn and R. S. Siegler (eds.) and W. Damon (series ed.) *Handbook of child psychology: vol. 2. Cognition, perception, and language*. New York: Wiley.

Case, R., Okamoto, Y., with Griffin, S., McKeough, A., Bleiker, C., Henderson, B. and Stephenson, K. M. (1996). *The role of central conceptual structures in the development of children's thought. Monographs of the Society for Research in Child Development*, *61* (5–6, serial no. 246).

Commons, M. L., Trudeau, E. J., Stein, S. A., Richards, F. A. and Krause, S. R. (1998). Hierarchical complexity of tasks shows the existence of developmental stages. *Developmental Review*, *18*, 237–78.

Corrigan, R. (1983). The development of representational skills. In K. W. Fischer (ed.) *Levels and transitions in children's development. New directions for child development*, *21*, 51–64. San Francisco: Jossey-Bass.

Dawson, T. L. (2001). A comparison of three developmental stage scoring systems. *Journal of Applied Measurement*, *3*, 146–89.

(2002). New tools, new insights: Kohlberg's moral reasoning stages revisited. *International Journal of behavior Development*, *26*, 154–66.

Dawson, T. L. and Gabrielian, S. (2003). Developing conceptions of authority and contract across the lifespan: two perspectives. *Developmental Review*, *23*, 162–218.

Demetriou, A., Christou, C., Spanoudis, G. and Platsidou, M. (2002). *The development of mental processing: efficiency, working memory, and thinking. Monographs of the Society for Research in Child Development*, *67* (1, serial no. 173).

DESIGNS (1994). *Proposal to the National Science Foundation*. Cambridge, MA: Harvard-Smithsonian Center for Astrophysics.

Detterman, D. K. (1993). The case for the prosecution: transfer as an epiphenomenon. In D. K. Detterman and R. J. Sternberg (eds.) *Transfer on trial: intelligence, cognition, and instruction* (pp. 1–24). Norwood, NJ: Ablex.

Driver, R., Guesne, E. and Tiberghien, A. (1985). Some features of children's ideas and their implications for teaching. In R. Driver, E. Guesne and A. Tiberghien (eds.) *Children's ideas in science* (pp. 193–201). Milton Keynes: Open University Press.

Driver, R., Squires, A., Rushworth, P. and Wood-Robinson, V. (1994). *Making sense of secondary science: research into children's ideas*. London: Routledge.

Ferrari, M. and Sternberg, R. J. (1998). The development of mental abilities and styles. In D. Kuhn and R. S. Siegler (eds.) and W. Damon (series ed.), *Handbook of child psychology: vol. 2. Cognition, perception, and language* (5th edn, pp. 899–946). New York: Wiley.

Fischer, K. W. (1980a). Learning and problem solving as the development of organized behaviour. *Journal of Structural Learning*, *6*, 253–67.

(1980b). A theory of cognitive development: the control and construction of hierarchies of skills. *Psychological Review*, *87*, 477–531.

Fischer, K. W. and Bidell, T. R. (1998). Dynamic development of psychological structures in action and thought. In R. M. Lerner (ed.) and W. Damon (series ed.) *Handbook of child psychology: vol. 1. Theoretical models of human development* (5th edn, pp. 467–561). New York: Wiley.

Fischer, K. W., Bullock, D., Rotenberg, E. J. and Raya, P. (1993). The dynamics of competence: how context contributes directly to skill. In R. Wozniak and K. W.

Fischer (eds.) *Development in context: Acting and thinking in specific environments* (pp. 93–117). Hillsdale, NJ: Erlbaum.

Fischer, K. W. and Connell, M. W. (2003). Two motivational systems that shape development: epistemic and self-organizing. *British Journal of Educational Psychology: Monograph Series II*, *2*, 103–23.

Fischer, K. W. and Corrigan, R. (1981). A skill approach to language development. In R. Stark (ed.) *Language behavior in infancy and early childhood* (pp. 245–73). Amsterdam: Elsevier.

Fischer, K. W. and Granott, N. (1995). Beyond one-dimensional change: parallel, concurrent, socially distributed process in learning and development. *Human Development*, *38*, 302–14.

Fischer, K. W. and Hogan, A. E. (1989). The big picture for infant development: levels and variations. In J. J. Lockman and N. L. Hazen (eds.) *Action in social context: perspectives on early development* (pp. 275–305). New York: Plenum Press.

Fischer, K. W., and Immordino-Yang, M. H. (2002). Cognitive development and education: from dynamic general structure to specific learning and teaching. In E. Lagemann (ed.) *Traditions of scholarship in education*. Chicago: Spencer Foundation.

Fischer, K. W. and Pipp, S. L. (1984). Process of cognitive development: optimal level and skill acquisition. In R. J. Sternber (ed.) *Mechanisms of cognitive development* (pp. 450–80). New York: Freeman.

Fischer, K. W. and Rose, S. P. (1996). Dynamic growth cycles of brain and cognitive development. In R. Thatcher, G. R. Lyon, J. Rumsey, and N. Krasnegor (eds.) *Developmental neuroimaging: mapping the development of brain and behavior* (pp. 263–79). New York: Academic Press.

Fischer, K. W. and Silvern, L. (1985). Stages and individual differences in cognitive development. *Annual Review of Psychology*, *36*, 613–48.

Fischer, K. W., Yan, Z. and Stewart, J. (2003). Adult cognitive development: dynamics in the developmental web. In J. Valsiner and K. Connolly (eds.) *Handbook of developmental psychology* (pp. 491–516). Thousand Oaks, CA: Sage.

Flavell, J. (1982). On cognitive development. *Child Development*, *53*, 1–10.

Granott, N. (2002). How microdevelopment creates macrodevelopment: reiterated sequences, backward transitions, and the zone of current development. In N. Granott and J. Parziale (eds.) *Microdevelopment: transition processes in development and learning*. Cambridge, UK: Cambridge University Press.

Granott, N., Fischer, K. W. and Parziale, J. (2002). Bridging to the unknown: a transition mechanism in learning and problem-solving. In N. Granott and J. Parziale (eds.) *Microdevelopment: transition processes in development and learning* (pp. 131–56). Cambridge, UK: Cambridge University Press.

Granott, N., and Parziale, J. (eds.) (2002). Microdevelopment: transition processes in development and learning. Cambridge, UK: Cambridge University Press.

Griffin, M. M. (1995). You can't get there from here: situated learning, transfer, and map skills. *Contemporary Educational Psychology*, *20*, 65–87.

Griffin, S. and Case, R. (1997). Rethinking the primary school math curriculum. *Issues in Education: Contributions from Educational Psychology*, *3*(1), 1–49.

Harvard-Smithsonian Center for Astrophysics (1997). *Minds of our own*. Science Education Department, Science Media Group. Cambridge, MA.

Horn, J. L. and Hofer, S. M. (1992). Major abilities and development in the adult period. In R. J. Sternberg and C. A. Berg (eds.) *Intellectual development* (pp. 44–99). Cambridge, UK: Cambridge University Press.

Jacobs, Kawanaka and Stigler (1999). Integrating qualitative and quantitative a pproaches to the analysis of video data on classroom teaching. *International Journal of Education Research*, *31*, 717–24.

Lakoff, G. (1987). *Women, fire, and dangerous things: what categories reveal about the mind*. Chicago: University of Chicago Press.

Lakoff, G. and Johnson, M. (1980). *Metaphors we live by*. Chicago: University of Chicago Press.

Lave, J. (1993). Word problems: a microcosm of theories of learning. In P. Light and G. Butterworth (eds.) *Context and cognition: ways of learning and knowing* (pp. 74–92). Hillsdale, N.J.: Lawrence Erlbaum Associates.

Martin, M. O., Mullis, I. V. S., Gonzalez, E. J., Smith, T. A. and Kelly, D. L. (1999). *School contexts for learning and instruction: IEAS third international mathematics and science study (TIMSS)*. Chestnut Hill, MA: Boston College.

Nardi, B. (1996). Studying context: a comparison of activity theory, situated action models, and distributed cognition. In B. Nardi (ed.) *Context and consciousness: activity theory and human-computer interaction* (pp. 69–102). Cambridge, MA: MIT Press.

Novak, J. D. and Gowin, D. B. (1984). *Learning how to learn*. New York: Cambridge University Press.

National Research Council (1996). *National Science Education Standards*. Washington DC: National Academy Press.

(1999). *How people learn: bridging research and practice*. M. Donovan, J. Bransford, and J. Pellegrino (eds.) Washington DC: National Academy of Science.

(2001). *Knowing what students know: the science and design of educational assessment*. Washington DC: National Academy Press

Novak, J. D. (1987). *Proceedings of the second international seminar: misconceptions and educational strategies in science and mathematics July 26–29, 1987*, vol II. Ithaca, NY: Department of Education, Cornell University.

Parziale, J. (2002). Observing the dynamics of construction: children building bridges and new ideas. In N. Granott and J. Parziale (eds.) *Microdevelopment: transition processes in development and learning* (pp. 131–56). Cambridge, UK: Cambridge University Press.

Parziale, J. and Fischer, K. W. (1998). The practical use of skill theory in classrooms. In R. J. Sternberg and W. M. Williams (eds.) *Intelligence, instruction and assessment* (pp. 96–110). Hillsdale, NJ: Lawrence Erlbaum Associates.

Pea, R. D. (1993). Practices of distributed intelligence and designs for education. In G. Salomon (ed.) *Distributed cognitions: psychological and educational considerations* (pp. 47–87). Cambridge: Cambridge University Press.

Perkins, D. N. (1997). *Knowledge as design*. Mahwah, NJ: Erlbaum.

Piaget, J. (1950). *The psychology of intelligence* (M. P. D. E. Berlyne, Trans.). New York: Harcourt Brace. (Originally published, 1947).

(1952). *The origins of intelligence in children* (M. Cook, trans.). New York: International Universities Press (originally published, 1936).

(1983). Piaget's theory. In P. M. Mussen (ed.), *Handbook of child psychology* (vol. 1, pp. 103–28). New York: Wiley.

Rogoff, B. (1990). *Apprenticeship in thinking*. New York: Oxford University Press.

Rose, S. P. and Fischer, K. W. (1998). Models and rulers in dynamical development. *British Journal of Developmental Psychology*, *16* (pt 1), 123–31.

Sadler, P., Coyle, H. and Schwartz, M. (2000). Engineering competitions in the middle school classroom: key elements in developing effective design challenges. *Journal of the Learning Sciences*, *9*, 299–327.

Salomon, G. and Perkins, D. N. (1989). Rocky roads to transfer: rethinking mechanisms of a neglected phenomenon. *Educational Psychologist*, *24*, 113–42.

Schwartz, M. (1998). The role of standard designs in goal setting in a science activity. Unpublished Qualifying Paper, Harvard University. Cambridge: MA.

(2000). Design challenges: a new path to understanding science concepts and skills. Unpublished doctoral dissertation. Harvard Graduate School of Educatin. Cambridge, MA.

Schwartz, M. and Sadler, P. (2001). *Goals and technology education: the example of design challenges*. Proceedings of the Second AAAS Research in Technology Education Conference. AAAS: Washington, DC.

(in press). Using a microdevelopmental framework to design a science curriculum. *Journal of Research in Science Teaching*.

Shamos, M. H. (1995). *The myth of scientific literacy*. New Brunswick: Rutgers University Press.

Shipstone, D. (1985). Electricity in simple circuits. In R. Driver, E. Guesne and A. Tiberghien (eds.) *Children's ideas in science* (pp. 33–51). Milton Keynes: Open University Press.

Vygotsky, L. (1978). *Mind in society: the development of higher psychological processes* (Cole, M., John-Steiner V., Scribner, S., Souberman, E, trans.). Cambridge, MA: Harvard University Press.

Werner, H. (1948). *Comparative psychology of mental development*. New York: Science Editions.

Wertsch, J. V. and Stone, C. A. (1978). Microgenesis as a tool for developmental analysis. *Quarterly Newsletter of the Laboratory of Comparative Human Cognition*, *1*(1), 8–10.

Yan, Z. and Fischer, K. W. (2002). Always under construction: Dynamic variations in adult cognitive development. *Human Development*, *45*, 141–60.