3

The Rhythms of Scientific Thinking: A Study of Collaboration in an Earthquake Microworld

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In this chapter we explore how people build new theories in the context of collaborative scientific thinking. As illustrated by many of the chapters in this volume, our default notion of "scientific thinking" has changed from that of the lone scientist or student toiling away on a magnum opus or in the laboratory, to that of people working as part of collaborative groups who negotiate goals for the task, co-construct knowledge, and benefit from the diverse prior knowledge that each collaborator brings to the table. In some ways, conceptualizing scientific thinking as fundamentally collaborative is not new. There are famous stories of how collaboration has played an important role in many scientific breakthroughs, from the discovery of the structure of DNA (Watson, 1968) to pioneering work in Artificial Intelligence (Simon, 1996). Furthermore, the goal of creating learning environments that support rich collaboration has also been at the heart of many innovations in science education.

Yet, psychologists who study scientific thinking from a cognitive perspective have only recently begun asking questions about how scientific understanding occurs within collaborative groups. One research direction has involved demonstrating that group work leads to greater conceptual change than individual activity. For example, Okada and Simon (1997) showed that pairs of undergraduate science majors were more successful than singletons in discovering scientific laws governing a computer microworld, while studies with children and adolescents suggest that working with a peer is more likely to promote mastery of a variety of scientific concepts than working alone (Kuhn & Phelps, 1979; 1982; Teasley, 1995). A second research direction has involved in-depth analyses of the group process to try to identify factors that facilitate or undermine shared scientific thinking. Coleman (1998), for example, investigated how expertise, gender, and social status influenced collaboration and learning, Forman and Larreamendy-Joerns (1995) assessed how the ongoing negotiation of problem solving goals related to successful and unsuccessful collaborations, and Azmitia and Montgomery (1993), Bianchini (1997), Dunbar (1997), and Suzuki (1994) studied the relation between role negotiation (i.e., each collaborator's responsibilities), features of dialogues (e.g., conflict and consensus, explanation, elaboration, synthesis, and analogy), and the processes and outcomes of collaborations.

In this chapter, we build on this research to describe the growth of scientific understanding as reflecting the rhythm of relatively individual and social moments of thought. The collaborative cognition of conversations and the individual insights from solitary reflection are both common characteristics that contribute to discovery and theory building in science. By referring to *relatively individual moments of thought,* we want to underscore the fact that scientists are never truly alone. They may be working by themselves in their laboratories, homes, or offices, but their thoughts are contextualized by those of others and by cultural tools and artifacts, such as the cannons of the scientific method and word processors (Cole, 1996; Wertsch, 1991). Conversely, even when members of a group sit across a table in face-to-face collaboration, it is only a *relatively social moment of thought*. Collaborators do not have complete access to the contents of each other's minds and must reveal their thoughts through talk or action to construct a shared understanding. Collaborators may also disengage temporarily from social interaction to either work out a new idea or to reduce frustration when collaborations do not proceed smoothly. Indeed, we have come to believe that, more often than not, collaborations, especially those that extend over time, are characterized by periods of engagement, disengagement, and re-engagement that may or may not be marked explicitly by the collaborators.

The structure of the chapter is as follows: We begin by selectively summarizing theoretical and empirical evidence for the interplay between relatively individual and social modes of thinking, discovery, and understanding. After reviewing the microgenetic methodology that allowed us to study this interplay, we describe the social mechanisms of change we investigated in our research. Then, we present research in which we studied the relation between relatively individual and social modes of scientific thinking while adult friends collaborated to build tall towers that could withstand the lateral forces of a simulated earthquake.

We map the nature of the changes in their theories about the task and then discuss the relation between these changes and what transpired during their collaborations. Finally, to illustrate further the social context of theory building and change, we present two case studies, one of a pair who solved the problem successfully and one of a pair who did not.

Scientific Understanding as a Relatively Individual and Relatively Social Process

The view that discovery and theory change require a delicate interweaving of relatively individual and relatively social processes has been proposed by scholars studying a wide range of phenomena. Because of space limitations, we only consider two of these programs of research. We review work exploring the role of peer collaborations in the mastery of Piagetian concepts because Piaget's theory has played a central role in studies of conceptual development and scientific understanding, and because researchers in this tradition typically include individual and collaborative assessments in their research. Because the timing of the individual and collaborative sessions is controlled by the experimenter, however, this work cannot inform us about how individual and social processes are naturally interwoven in scientific thinking. Research that has documented the process of creative insight addresses this issue, and thus, we included it as our second example of the relatively individual and social rhythms of science.

In the late 1970s and early 1980s, the Social Genevans (e.g., Doise & Mugny, 1984; Perret-Clermont, 1980) devoted considerable attention to studying the cognitive consequences of peer collaborative problem solving. Their motivations were both theoretical and applied. Theoretically, they wanted to re-examine the claim that Piaget had made in his studies of moral development in the 1930s, that conflicts about ideas that occur during interactions between relative equals, i.e., peers, can provoke the cognitive disequilibrium that is a prerequisite for conceptual change. They reasoned that if they were able to demonstrate this empirically in the laboratory and develop procedures to evoke disequilibrium reliably, they would be able to apply their work to peer collaborative learning in the classroom. Perret-Clermont, in particular, was also interested in whether forming collaborative peer groups that included economically and socially-advantaged and disadvantaged children would reduce or eliminate differences in academic performance and conceptual understanding that are often evident in the cognitive performance of children of different socioeconomic backgrounds.

While these studies explored a variety of Piagetian concepts such as conservation, perspective taking, and isolation of variables, they generally shared the same experimental design: Participants were given an individual pretest, randomly assigned to either work alone (the control condition) or with partners (the experimental condition), and, finally, given an individual posttest. Researchers used changes in individuals' performance from the pretest to the posttest to infer conceptual change.

Because in our research we have been interested in the patterning of relatively social and relatively individual understanding over time, the studies that are especially relevant to us are those in which participants received an immediate and a delayed individual posttest following the collaborative session. These studies revealed that the cognitive gains that accrued from the collaboration often increased from the immediate to the delayed posttest. The researchers concluded that their findings supported Piaget's claim that the cognitive restructuring that follows disequilibration can take some time to materialize because intramental processes and knowledge need to be recalibrated. The recalibration process is captured by Piaget's definition of equilibration, Damon's percolation metaphor (personal communication, October, 1996), and Draper's discussion of fermentation (Laboratory of Comparative Human Cognition electronic discussion, 1989). Unfortunately, although these explanatory constructs and metaphors are provocative, there is little empirical documentation of how exactly they operate to produce conceptual change.

Although the specifics of equilibration, percolation, or fermentation remain fairly obscure, recent research has replicated and extended Perret-Clermont's, Doise's, and Mugny's early finding of the social-constructive nature of conceptual change. Howe, Tolmie, and Rogers (1992) and Tolmie, Howe, Mackenzie, and Greer (1993) used immediate and delayed posttests in their studies of how elementary schoolchildren's collaborations promoted or impeded their understanding of concepts such as buoyancy. Their results showed that not only was conceptual change greater in the delayed than the immediate posttests, but that individuals also produced ideas that were not discussed in the collaboration or stated in the immediate posttest. At first glance, the emergence of new ideas in the delayed posttest could be taken to support the view espoused by Piaget that individual restructuring and recalibration is more important for cognitive growth than what transpires in the collaborative context. However, when the researchers analyzed the collaborative sessions, they found that the individuals who generated new ideas and made the most gains in understanding from the immediate to the delayed posttest were members of groups in which partners had refined, extended, and challenged each others' ideas during collaboration. Members of groups in which individuals had merely stated their views, conflicts had gone unresolved, or partners had been unable to establish a shared frame of reference showed the least amount of progress and produced fewer new ideas from the immediate to the delayed posttests. Taken together, the results of these studies add to the growing literature (for a review, see Rogoff, 1998) that the substance of what transpires in the collaboration plays an important role in conceptual growth (or lack-thereof) and support our proposal that theory development accrues from both relatively individual and relatively social modes of reasoning.

In a more naturalistic situation, Csikszentmihalyi and Sawyer (1995) illustrated the dynamics of individual and social rhythms in their work on how creative insight—usually considered an intramental process—occurs within social contexts. Csikszentmihalyi and Sawyer interviewed 60 people nominated by their peers as especially creative in their fields (e.g., political and environmental activism, business, the arts, and a variety of academic disciplines). In their extensive retrospective interviews, these individuals recounted the process through which they produced their best work. Csikszentmihalyi and Sawyer's content analyses of nine of these interviews (an environmental activist, two physicists, a banker, a mathematician, an economist, a literary critic, an expert in ceramics, and a sculptor) suggested that creative insight was the result of a four-stage process. The first stage included a period of intense hard work and research; the second stage a period of idle time spent alone, often in activities unrelated to the creative activity (e.g., gardening, taking a walk); the third stage the moment of insight itself; and the fourth stage a return to hard work to bring the insight to fruition. Csikszentmihalyi and Sawyer's interviewees reported that during the periods of hard work that preceded and followed their insights, they frequently interacted with colleagues to propose and discuss ideas. Eventually, however, the social context saturated their thinking and they needed to engage in solitary reflection to make sense of the social discourse.

In considering why researchers who are interested in creativity (e.g., Martindale, 1990) have usually drawn on the intramental cognitivist tradition and disregarded the social and cultural context of scientific and artistic creativity (but see Harrington, 1990; John-Steiner, 1992), Csikszentmihalyi and Sawyer (1995) stated:

> When we look at the complete "life span" of creative insight in our sub-

> jects' experience, the moment of insight appears as but one short flash in the complex, time-consuming, fundamentally social process. It is true that the individuals we interviewed generally report their insights as occurring in solitary moments: During a walk, while taking a shower, or while lying in bed just after waking. However, these reports usually are embedded within a more complex narrative, a story that describes the effort preceding and following the insight, and the overall sense of these complete narratives stresses the salience of social, interactional factors. It seems that the solitary nature of the moment of insight may have blinded us to the social dimension of the entire creative process. (p. 331)

Microgenesis and Scientific Reasoning

As noted earlier, while the work of the Social Genevans demonstrated the interplay between intramental (i.e., individual) and intermental (i.e., interpersonal) components of cognitive change, it only revealed products, not processes of change. Csikszentmihalyi and Sawyer's research does speak to this issue, but the phenomena of interest emerged over a fairly long period of time and under unpredictable, uncontrollable circumstances; most researchers do not have the resources to carry out this research (but see Dunbar, 1995; 1997; this volume). An additional limitation of this work is that it is based solely on self-reports; these self-reports may omit or distort some of the processes of interest. In our view, the microgenetic methodology represents a reasonable compromise for observing the interplay between individual and social rhythms of scientific discovery and theory change.

The microgenetic methodology involves carrying out fine-grained analyses of changes in behaviors (e.g., dialogues, strategies) over the course of one or several sessions. Researchers assume that these changes reflect moment-to-moment learning and development in a particular problem-solving context and thus, index what may be occurring within the unobservable confines of people's minds (Klahr & MacWhinney, 1998; Rogoff, 1998). Microgenetic analyses do not require that participants achieve complete mastery of the task; all that is required is that some change, whether progression or regression, occur (Kuhn & Phelps, 1979). In many cases, one of the goals of these studies is to accelerate change by giving participants repeated opportunities to engage in the concepts, skills, or strategies under investigation to ensure that the researchers will be able to map the patterns of change (Kuhn, 1995; Siegler & Crowley, 1991).

Because of its potential to reveal learning and development, the microgenetic methodology has been employed by researchers from a wide variety of theoretical approaches to conceptual development. Working from a neo-Piagetian constructive orientation, for example, Kuhn, Amsel and O'Loughlin (1988) and Schauble (1996) explored how individual children, adolescents, and adults learned to coordinate scientific theory with evidence over the course of several sessions in which they attempted to isolate variables responsible for a variety of scientific phenomenon. Within the information processing approach, Siegler (1996) has employed this methodology to study how individual children acquired mathematical strategies over time. Finally, in contrast to scholars focusing on individual problem solving, researchers in the sociocultural tradition have focused their efforts on mapping microgenetic changes that occur in situations when pairs or groups work together on a variety of tasks such as classifying objects (Ellis & Rogoff, 1992), story book reading (Edwards & García, 1999), putting together puzzles (Wertsch, Minick, & Arns, 1984), or developing and testing causal hypotheses in the laboratory (Azmitia & Montgomery 1993) or the classroom (Greeno & Goldman, 1998).

Microgenetic studies of individual problem solving have shown that development is gradual and uneven, characterized by progressions and regressions in both strategy use and conceptual understanding. At any point in time, individuals apply multiple strategies to a problem and hold a variety of beliefs that may or may not be consistent with each other. Also, less adequate strategies and beliefs coexist with better ones (Kuhn, 1995; Siegler, 1996). Kuhn and Phelps (1982) found that one of the major impediments to learning was not the absence of sufficient knowledge or sophisticated strategies, but rather, the difficulties that people experienced in giving up inaccurate beliefs and inefficient but familiar problem solving strategies. Their findings challenged the prevalent view that theory development occurs primarily through the addition of information (for a more extensive discussion of this issue and about whether or not this methodology is informative concerning 'natural' change processes, see Kuhn, 1995). Having a partner (or partners) can remove or reduce resistance to relinquish ineffective strategies when individuals are exposed to alternative perspectives, are asked to clarify and justify their views, or are able to observe others' problem solving (Azmitia, 1996; Crowley & Siegler, 1999; Dunbar, 1995; Finholt & Olson, 1997; Hatano, 1994; Kobayashi, 1994; Latour & Woolgar, 1979). Thus, solving problems in a social context can accelerate change; while both singletons and teams eventually formulate correct hypotheses and solutions, teams often reach this goal sooner (Teasley, 1995; but see Okada & Simon, 1997).

Studies of dyadic or group problem solving have shown that positive change is more likely when collaborators have different but overlapping backgrounds and knowledge (Dunbar, 1995; Kobayashi, 1994) and are able to establish a joint frame of reference and shared goals (Rogoff, 1998; Teasley & Rochelle, 1993; Tharp & Gallimore, 1988). Developing this shared understanding, however, does not imply that reaching consensus is necessary or sufficient for theory change; dissension can also serve as a catalyst for progress either during or following the collaborative session (Azmitia & Montgomery, 1993; Matusov, 1996).

Finally, the nature of collaborators' dialogues plays an important role in microgenetic change. For example, *transactive dialogues*, which are conversations in which partners critique, refine, extend, and paraphrase each other's actions and ideas or create syntheses that integrate each other's perspectives, have been linked to shifts in both moral reasoning (Berkowitz & Gibbs, 1983; Kruger, 1992) and scientific understanding (Azmitia & Montgomery, 1993; Howe et al., 1992). These transactive dialogues may be the epitome of collaborative theory construction because in many cases, individuals walk away with a joint product for which they are no longer certain (and may not care) who gets credit for particular ideas (for a more extended discussion of this phenomenon, see Bos, 1934; John-Steiner, 1985). Proffering *explanations* during social discourse has also been associated with conceptual change in a variety of domains, including emotion (Cervantes & Callanan, 1998) and science (Okada & Simon, 1997; Teasley, 1995). This work on explanations converges with findings from research (e.g., Chi, de Leeuw, Chiu, & LaVancher, 1994; Crowley & Siegler, 1999) demonstrating the importance of self-explanations for problem solving. Finally, *analogies* that are used to provide explanations, design or refine experiments, and formulate hypotheses also play an important role in scientific discovery and theory change (Dunbar, 1995; 1997).

In our research, we explored collaborators' use of transacts, explanations, and analogies while they collaborated on a design task. We were interested in the functions of these utterances during the problem-solving process and in their association with hypothesis generation, theory change, and problem solving success.

A Microgenetic Study of Collaborative Scientific Understanding

We now turn to a study in which we used the microgenetic method to trace changes in individuals' and pairs' understanding in a task that draws on participants' knowledge of earthquakes. We observed changes in their theories about the task over a series of four individual and two collaborative sessions. The collaborative sessions were spaced one week apart and each collaborative session was preceded and followed by an individual session, yielding four relatively individual assessments. We considered the four individual assessments to be relatively individual windows into participants' understanding because the experimenter posed questions that required participants to reflect upon and externalize their theories about the task. We controlled the timing of the sessions, so we cannot speak to processes that occurred outside of our periods of observation and cannot claim that we were mapping the natural timeline of conceptual change in this task. However, by providing opportunities for collaboration and individual reflection, we implemented a gross manipulation of the flow of individual and collaborative moments that have been shown to characterize theory building and revision in previous work (e.g., Csikszentmihalyi & Sawyer, 1995; Dunbar, 1995; 1997).

Our collaborative sessions reflected the convention of organizing ongoing research around scheduled meetings where team members assemble with the explicit goal of working together on a problem. In his study of scientific discovery in real-world laboratories, Dunbar (1995; 1997; this volume) provided in-depth analyses of these structured activities. An additional way in which we tried to model real-world collaboration is that our participants were friends and had worked together on projects in the past, much like scientists who at the very least have a working relationship. We did not use the individual sessions in the traditional sense of pretests and posttest, i.e., as measures of task mastery. Rather, we used them to provide individuals with opportunities for reflection and to gather snapshots of their theories that allowed us to assess the functions of collaboration in theory development and change. We were especially interested in whether partners used the collaborative sessions to confirm ideas and hypotheses for which they had already gathered evidence (i.e., ideas that were already part of their theories) or whether they used these sessions to develop new ideas.

Twelve pairs of undergraduate friends participated in the study. We chose the domain of earthquakes because it is a standard unit in the elementary school and high school science curriculum and because we anticipated that their personal experiences with earthquakes would be part of our California participants' informal knowledge (all reported that they had experienced at least one earthquake).

In most laboratory studies of collaborative scientific reasoning, participants work on tasks in which they manipulate a small set of established parameters to isolate the ones responsible for the phenomenon. These tasks often also have either a single or at least an ideal solution. These features rarely characterize the open-ended problems of everyday scientific practices. In the "real world," before carrying out controlled tests of hypotheses, scientists have to identify the relevant variables and construct a language to talk about variables and outcomes. Even if they attain this goal, it may not be possible to design a controlled test to choose between competing theories and if controlled tests can be devised, feedback can be error-laden and there may be more than one satisfying solution to the problem.

The earthquake task is an open-ended task that shares many of these complexities. The earthquake machine is a device that shakes a platform back and forth to generate a simulated earthquake; our device is similar to earthquake machines used in demonstrations in university earth science courses and science museums. Participants use foam blocks to build towers that will withstand the simulated earthquake.

As is the case for everyday scientific problems, there are multiple strategies for designing towers that withstand the simulated earthquake. The problem is also of interest because it cannot be tackled efficiently with a systematic control of variables strategy (see Klahr, Chen, & Toth, this volume). Unlike steel or wood frames in real buildings, the block towers are compression structures. Blocks are held together by gravity and friction rather than bolts or nails. Thus, adjacent blocks do not necessarily respond as a single unit to the same lateral forces. The individual square blocks respond unpredictably because their shapes generate additional impacts each time they rock back and forth on their flat bases.

However, the difficulty of obtaining precise quantitative predictions does not mean that there is nothing to learn and measure in this task. The cathedrals of Europe are, in essence, nothing more than stacks of independent stone blocks held together by gravity and friction. Without the ability to make precise quantitative predictions, their architects were able to erect structures which have, for several hundred years, successfully resisted the toppling influence of winds, and, in some cases, earthquakes. What is responsible for the continued stability of these buildings is exactly what guided our participants' design of block buildings: Their theories about structural stability, we hypothesized, would be created through a mix of intuition, analogy to existing buildings, experiences building with blocks or stacking objects such as books, and structural experimentation.

The sessions were videotaped and transcribed. In each relatively individual session, we assessed participants' current theories by first giving them 12 foam blocks and asking them to build a tower that they thought would withstand the earthquake. After they built their tower, we asked them to explain its strengths and weaknesses. Finally, we showed them pictures of block towers others had built. For each picture, we asked participants to predict whether the tower would remain standing after being subjected to the simulated earthquake and to list its strengths or weaknesses. In the collaborative sessions, pairs were given 12 foam blocks and asked to build a six-story tower that would withstand the simulated earthquake. The side of a block was equivalent to one story. They were told they would have had 15 minutes and to build and test as many towers as they wished. When they were ready to test a tower, they pressed a button that caused the machine to produce a five second earthquake. If they succeeded before the end of the session, they called the experimenter to witness another test of their tower and were given four more blocks and a new goal (eight stories).

Building stable towers on the earthquake machine was not a trivial task for the undergraduates. Three pairs achieved the goal of building a stable six-story tower in the first session and two more achieved this goal in the second session; no pair was able to build an eight-story tower that withstood the five-second simulated earthquake, although one pair built an eight story tower that stood for four seconds. While the seven remaining pairs did not achieve success by our experimenter-imposed standards, they were all able to build stable five-story structures by the end of either the first or second collaborative session.

Theory Change

To assess changes in participants' individual theories, we tracked six structural features over the course of the two sessions. We identified participants' *implicit theories* by coding the features that appeared in the towers they built in the individual theory assessments and the collaborative sessions. We identified participants' *explicit theories* by coding what they told the experimenter about their towers in the individual sessions and what they talked about with their partner during collaboration. Three of the six features we coded were global properties of the whole structure:

1. *Expanded Base*: The base should be wider than the top.
2. *Symmetry*: The building should be symmetric in at least one dimension around the central axis.
3. *Two Dimensions (2D):* The building does not need to expand more than one block perpendicular to the direction of motion.[1]

Three features characterized local building techniques within the structure:

4. *Cross Bracing*: Use of post-and-beam bracing (one block lying across the top of two others).
5. *Closed Gaps*: Blocks in the same story of the building should be touching each other rather than spaced apart.
6. *Stories-in-Line*: Blocks in subsequent stories should be flush rather than sticking out at different angles.

Changes in Implicit Theories

At the beginning of each of the four individual assessments, participants were asked to build a tower that they thought could withstand the earthquake. The three global features were coded as either present or absent. The three local features were coded as being present on few (zero to 33% present), some (34% to 66%), or many (67% to 100%) of the stories in the tower. Figure 1 shows changes in feature use for each participant across the four theory assessments.

Participants began the study (T1 column in Figure 1) by building towers that incorporated a range of features. The most common global feature was symmetry (92% of the towers), followed by expanded base (71%). In contrast, the other global feature, 2D, characterized only 10% of the first buildings. The most common local feature was stories-in-line, with 92% of the towers having many stories in line, 8% having some stories in line, and no towers having only a few. Closed gaps were also com-

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[1] In the "real world," earthquakes create lateral and perpendicular movements and thus, buildings need to be three dimensional. Because the earthquake machine only moved laterally, however, buildings only needed to extend along the direction of this lateral movement, in two dimensions.

mon (62% many, 21% some, 17% few) while cross-bracing was less common (37% many, 21% some, 42% few).

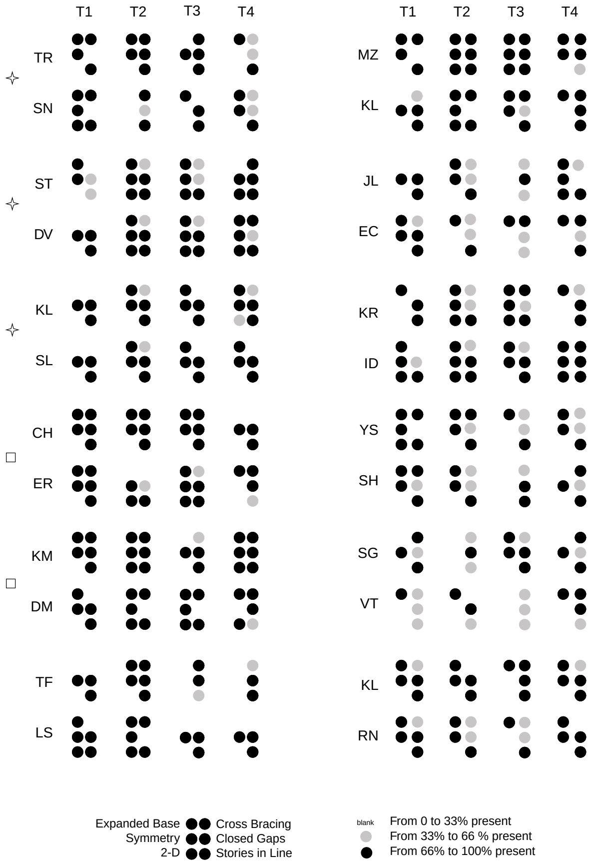

Figure 1. Implicit theories for stable structures, as coded by the features characterizing towers built in each of the four individual interviews (T1, T2, T3, T4). Each tower was coded for six target structural features, represented here on a 2 X 3 grid. As shown in the figure legend, the left column of each grid represents three global features (expanded base, symmetry, 2D) coded as being either present (black dot) or absent (blank). The right column of each grid represents three local features (cross bracing, closed gaps, stories in line) coded as being present on few (blank), some (gray dot), or most (black dot). Stars indicate the three pairs who successfully built six-story towers that could withstand the simulated earthquake in session one. Squares indicate the two additional pairs who achieved this goal for the first time in the second session.

By the last relatively individual theory assessment in the study (the T4 column in Figure 1), the overall level of the six features exhibited some changes. For the global features, symmetry dropped from characterizing almost all towers to only 67%. Expanded base held steady at 75% while 2D grew somewhat to 25%. For the local features, prevalence of closed gaps within a tower held more or less steady (66% many, 29% some, and 4% few), while stories-in-line decreased somewhat (83% many, 17% some, and zero few). The largest changes in local features occurred in use of cross-bracing. In the first theory assessment (T1) it had been most common to have few joints cross-braced. However, by the end of the study (T4) only 17% of towers had few cross-braces while 50% had many and 33% had some.

The overall patterns underestimate the amount of change that occurred in particular individuals' theories. In fact, an examination of the individual participant patterns in Figure 2 reveals that it was quite uncommon for participants to maintain the same features on subsequent assessments: 91% of all towers differed in at least one feature from the tower built by the same person in the previous individual assessment. On average, participants made changes in about two of the six features between successive towers in the individual assessment. Interestingly, this rate of change was about the same within each of the sessions and across the two sessions. Thus, both the collaborative activity and the week off between sessions appeared to induce change.

We had anticipated that, over time, the collaboration would bring partners' individual theories closer, but we observed the opposite. In T1 (before the first collaborative session) the overall overlap between partners' implicit theories was about as large (72% of features shared) as it would ever get. The overlap at T2 was similar (74%), but overlap was markedly lower in T3 (58%) and T4 (60%). Thus, over time partners' implicit theories drifted apart.

Changes in Explicit Theories

After participants built towers in the individual theory assessments, the experimenter asked them to talk about the features of the tower that would help it withstand the earthquake. We coded their talk for mentions of each of the six features; this talk indexed their explicit theories for the task (Figure 2).

The first thing to notice about Figure 2 is that participants never talked about all six features when analyzing their buildings. In the first individual assessment, they mentioned an average of only 1.7 of the six target features. There was a significant increase in the number of different features participants talked about across the sessions, with means of 2.2, 2.5, and 2.7 features in T2, T3, and T4, but they still talked, on average, about less than half of the six features.

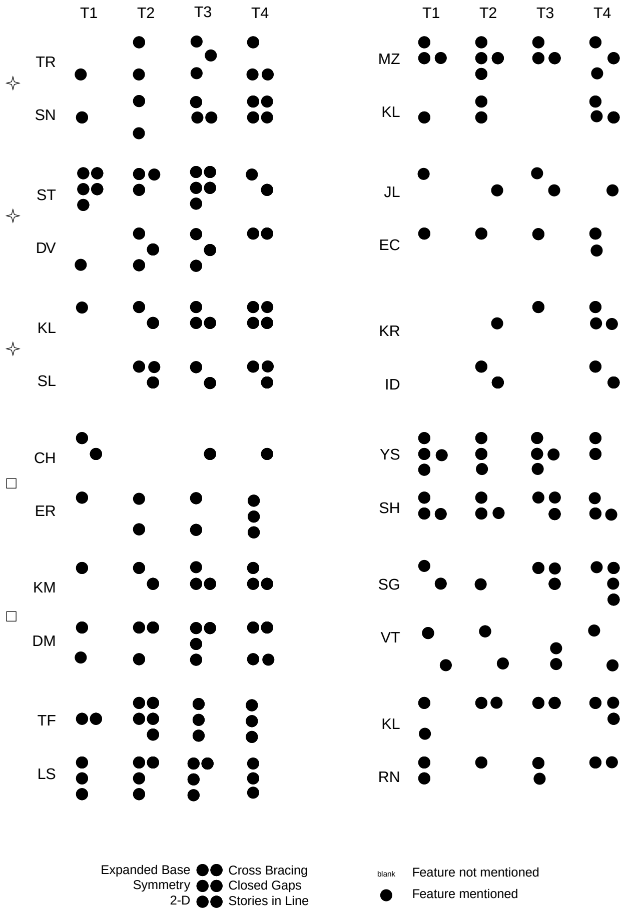

Figure 2. Subjects explicit theories for stable structures, as coded by the features of their towers that subjects talked about during each of the four individual interviews.

The most commonly-discussed global feature, and also the feature that was mentioned most often overall, was expanded base, which rose from 67% of the participants mentioning it in T1 to 92% in T4. Mentions of symmetry rose from 38% to 46%, but mentions of 2D support decreased from 29% in T1 to 25% in T4. All three local features showed increases over time: Spacing from 29% to 58%; cross-bracing from 4% to 33%; and stories-in-line from 4% to 17%.

Figure 2 shows that, as was true of individual participants' implicit theories, their explicit theories changed frequently between assessments, with 82% of theories changing by at least one feature. The mean rate of change was a little less than 1.5 features, which, because the average number of features in an explicit theory was about 2.5, amounts to more than half of the features changing from one individual assessment to the next. Again, similar to the case for implicit theories, changes in explicit theories were equally common within a session and between the sessions

In contrast to changes in implicit theories, which were as likely to involve feature addition as deletion, changes in explicit theories most often involved deleting old features. For four features (symmetry, two-dimensions, cross-braces, and closed gaps), 50% or more of the participants who included the feature in their theories on one assessment dropped it from their theories on a subsequent assessment. The feature that was most likely to be added and not deleted was expanded base; the only feature mentioned by everyone at least once and which was subsequently dropped by only 25% of participants. Stories-in-line was mentioned by just one participant before the fourth and final individual theory assessment, and she ended up dropping it from her final theory. The finding that participants were more likely to delete than add features is in contrast to Kuhn and Phelp's (1982) study, in which individuals resisted relinquishing old knowledge or strategies even when confronted by evidence of their inadequacy. However, our research differs from theirs in that the open-ended nature of the task did not lend itself well to systematic hypothesis testing and evaluation. Therefore, the frequent changes in tower features may reflect the trial-and-error approach adopted by many of our participants.

Similar to the case of implicit theories, partners' explicit theories were not more likely to become shared by the end of the study. We calculated the overlap in explicit theories by dividing the number of the six features that both partners had talked about in a given theory assessment by the total number of the six features mentioned by either partner. Overall, partners' explicit theories remained distinct across the study, rising only slightly from 35% shared on T1 to 47% on T4. Note that this overlap in explicit theories was always lower than had been the case for implicit theories.

The Social Context of Theory Change

All pairs began the first collaborative session by exploring the earthquake machine and sharing some of their beliefs about features. They also showed evidence of their mastery of the scientific practices that we teach in Western schools in several ways: While building their first few towers, they formulated hypotheses and tried to set up critical tests for them; they evaluated the results of these critical tests and used them to refine their hypotheses; and they discussed whether there was a correct (ideal) solution to the problem. However, in this particular task, such an approach is a hindrance because all the relevant variables are not known, the feedback is error-laden (in part because there is an element of luck in whether towers stand or fall), and there are numerous solution pathways. Moreover, time is limited, so building and testing as many towers as possible can lead to greater success than carrying out and evaluating a limited set of controlled tests. Over the course of their collaboration, all pairs came to realize this, and discontinued their critical tests of hypotheses. The three pairs who achieved the goal of six stories in the first session appear to have come to this realization earlier (i.e., by their second or third tower) than other pairs.

As discussed, prior research has revealed an association between constructing a shared understanding of the task and scientific discovery and theory change. Our preliminary analyses of participants' dialogues suggest that most partners were responding to and building on each other's ideas. Surprisingly, however, collaborators who succeeded in the task not only retained a significant number of unique ideas from their original individual theories, but failed to discuss these ideas with their partner. Because they built towers that contained these features, it may be that they were using the collaborative session, at least in part, to test and reflect upon their own ideas. Why they did not discuss their ideas with their friend is a question that deserves future study. Perhaps they reasoned that by using them in their buildings, they were communicating their views. Perhaps the knowledge remained an implicit part of their theories and they did not even know that they knew it.

We will assess the interplay between verbal and non-verbal communication of ideas in future analyses. In any case, our findings suggest that building an explicitly-shared theory was not necessary for making good progress on the task. This suggestion receives further support from our analysis of the discussions of our least successful pairs. After a series of unsuccessful towers, these pairs adopted a brainstorming strategy. Their lack of success on the task may have led them to discuss as many ideas as they could in an attempt to create a shared theory and succeed. It is possible that, given enough time, their discussion would have cohered into a narrower shared theory that would lead to success. However, a close examination of their discourse suggests that this brainstorming was not moving their theories forward. In particular, they seemed to be constrained by a problem of set (i.e., they returned to the same ideas time and time again even though they had already accumulated evidence that they did or did not work) and had trouble distinguishing between relevant and irrelevant information (i.e., their problem set was too large). These findings converge with those of other who have demonstrated that brainstorming can sometimes limit creativity and impede problem solving (for a review, see Lamm & Tromsdorff, 1973).

Thus far, we have contrasted the manipulation in which we forced individual and social modes of thinking to occur by asking pairs to work together or reflect relatively individually on the task. We now turn to a more naturalistic examination of individual and social processes, those which occurred during the collaborative session as partners disengaged and re-engaged in the collaboration. Our analysis of the interaction patterns of the twelve pairs who participated suggests that one function of disengagement was to modulate affect and frustration. The task is challenging, and partners often commented that they doubted whether it was possible. In 36% of the instances in which partners expressed frustration or reached an impasse, they disengaged from the collaboration and worked in parallel for some time. Another function of disengagement from the collaboration was for individuals to work on an idea that they would subsequently suggest to their partner or try on the earthquake machine. We had provided notepads and pencils to participants, and occasionally, one of them left his or her partner working on the machine and used the notepad to draw possible tower constructions or outline a building principle or feature of the machine. These solitary moments were relatively brief (seldom more than a minute), and partners soon returned to the collaboration to try the new idea or propose a compromise position, such as taking turns or testing both of their ideas to see which would be most successful. Thus, it appears that relatively individual rhythms can occur during collaboration when partners need to reduce negative affect, when they are engaged in a power or dominance struggle, or when they are trying to work out an idea of their own.

Social Mechanisms of Change

At present, we have completed the analyses of the collaborative dialogues of six pairs. The results of these analyses show that discussions in which partners used explanations and transacts (i.e., critiques, elaborations, clarifications, paraphrases, or syntheses of each other's ideas) sometimes led to feature addition in individual explicit theories, and deletion in the concurrent or subsequent towers the pairs built. However, these changes were not always carried over to the relatively individual theory assessments that followed collaboration. Interestingly, while feature deletion was more common than feature addition in the individual assessments, in the collaborative dialogues the opposite was true, feature addition was more likely than feature deletion. Thus, in this social, but not the individual, context, our findings supported Kuhn and Phelp's (1982) claim that one of the major impediments to learning involves giving up our old, inefficient ideas or strategies. Note, however, that this finding contradicts our earlier proposal that people may be more willing to relinquish ideas (in this case, delete features) during collaboration than during individual problem solving. Even though, as we proposed, their partners or the evidence pointed to the erroneous nature of their ideas, participants still resisted dropping features they believed in.

Although the finding that high level discussions can lead to theory change was consistent with our predictions and the results of previous research, it is important to note that the frequency of transacts and explanations was relatively low. It is possible that because the earthquake task is very visual (i.e., participants can share theories through building demonstrations), non-verbal interaction was as important as verbal exchanges in promoting theory change. We plan to explore this possibility after we analyze the dialogues of the remaining six pairs.

The six pairs we have analyzed also used analogies to bring their informal and formal knowledge to bear on the task. The most common analogies involved block-building (e.g., blocks, block-balancing games such as Jenga), relating the motion of the earthquake machine's platform to the movement of tectonic plates in real earthquakes, and comparing the movement of block towers on the machine to the movement of buildings during a real earthquake. Analogies were more frequent in the opening stages of collaboration, when partners were engaged in working to relate their extant informal and formal knowledge to the present task and develop a language to talk about the features of their towers and the machine. We also found that, like Dunbar's (1995; 1997) scientists, our participants used analogies to formulate hypotheses, design and evaluate experiments (i.e., test and evaluate tests of their block towers), and explain their findings.

An analogy that consistently led to theory change (i.e., the feature was deleted or added in participants' subsequent relatively individual theory assessments) involved partners' realizing that to withstand earthquakes in the real world, buildings need to be reinforced from all sides (three-dimensional support), although on the earthquake machine buildings only needed to be reinforced in the direction of the lateral movement of the building platform (2D support). For example, in their first collaborative session, ST shared with DV his view that to withstand the earthquake, the towers needed to be three-dimensional so they would be supported on all sides. DV countered that the machine moved laterally only in one direction, and thus, two-dimensional support was sufficient. This discussion may have been what led ST to delete this feature from his subsequent relatively individual theory assessments.

An analogy that did not consistently lead to individual theory change involved allusions to the ways in which cross-bracing supports buildings. In two of the pairs, individuals tried repeatedly to convince their partners about the importance of this feature. Even when they demonstrated how this feature strengthened a tower, their partners did not add the feature to their individual theories. Unlike Dunbar (1995), then, we did not find a simple relationship between analogy and theory change. Note, however, that Dunbar's study involved expert scientists working on problems over the course of a whole year. Our participants' domain knowledge and time was more limited, and these factors may have prevented them from taking full advantage of their partners' analogies. In one case, analogies actually hampered progress because partners generated a wealth of analogies and did not, like other pairs, discriminate between those that applied and those that did not apply to the task. Their plight is a nice illustration of Perkins' (1997) suggestion that to facilitate creativity and conceptual growth, analogy must be used selectively and judiciously. Finally, it is also possible that the analogies that our participants produced were not as sophisticated as those produced by Dunbar's expert scientists and thus, were less powerful agents of change.

Case Studies of Collaboration

We have presented some suggestive evidence that analogies, explanations, and transacts promoted theory change and problem solving success. However, the relationship between these sophisticated features of collaborative scientific discovery and problem solving success is not that simple, as the following two case studies of an unsuccessful and a successful pair illustrate. We selected these two pairs because they both began by trying to set up critical tests of hypotheses, they communicated their beliefs and tried to build a shared understanding of the task, they frequently used transacts, explanations, and analogies in their discussions, and they built and tested a similar number of towers in the first collaborative session. Note that by successful and unsuccessful we mean success in building a stable six-story tower. Both pairs were very successful in establishing a collaboration.

LS and TF, an Unsuccessful Pair

LS and TF began their first collaborative session by each stating and testing some of the features of their individual theories (expanded base and no spacing between the blocks, respectively). They also explored the machine's movement, placing blocks on the platform to determine the most stable location and discussing whether the orientation of the tower on the platform affected its stability. LS commented that she wished she could remember her physics so she could use physics principles to make the towers more stable. Most of LS's and TF's conversations and work during this session were devoted to the pros and cons of placing their towers in different locations on the earthquake platform and the best way to orient blocks on the different stories (these locations and orientations were also the focus their hypothesis testing). While LS did not state her belief that the stories needed to be lined up and TF did not state her view that symmetry was important, both built towers that contained these features, a finding that demonstrates once again the importance of non-verbal demonstrations for theory building, refinement, and testing in this task and in science in general.

Table 1. Explanations, analogies, transacts, and scientific methodology used by TF and LS in the first and second collaborative sessions.

LS and TF	Session 1	Session 2
Towers built and tested	10	29
Explanations of building features	7	5
Analogies	4	3
Transacts (critique, elaborate, synthesize)	5	3
Scientific Methodology		
Critical tests of hypotheses	4	2
% Tests evaluate and explain outcomes	30	34

As can be seen in Table 1, LS and TF explained why they believed particular features were building strengths or weaknesses, engaged in transactive dialogues in which they critiqued, clarified, and elaborated each other's reasoning, produced analogies (e.g., LS commenting on the movement of the machine as she watches their tower fall: "See, that's what earthquakes do, the first jolt isn't gonna do it, it's the last couple of seconds"), carried out critical tests of hypotheses (i.e., tested a tower with the feature and then a tower without the feature), and commented on the success and failure of their towers, although they only engaged in evaluative discussions of strengths and weaknesses of their towers after 30% of tests. During this first collaborative session, LS and TF also discussed features individually as well as holistically, i.e., how features interacted to produce stability or instability. Their discussions displayed the systematicity of the scientific method in that they kept track verbally of ideas they had tested to avoid repeating tests and their critical tests of hypotheses built on each other (e.g., after testing whether an expanded base was important, they tested whether an expanded base with spacing between the blocks was better than an expanded base without spacing between the blocks). Towards the end of the session, they considered whether the task was possible and acknowledged that there was an element of chance in whether towers stood or fell during the simulated earthquake.

Their second collaborative session was markedly different. They began with a brief discussion of towers that may work or fail on the earthquake machine and then decided to adopt a trial-and-error strategy to build and test more towers than they had in the first session (29 versus 10). This initial discussion was not related closely to the relatively individual theories they had espoused immediately prior to the second collaboration (i.e., the third relatively individual theory assessment). Rather, their discussion concerned the block-building they had carried out at home in preparation for this session and the pictures of towers they had seen in the preceding relatively individual theory assessment. Interestingly, after their first two towers failed, they redefined the goal of the task and spent the next eight minutes building and testing four or five story towers, alternating between systematic critical tests of hypotheses about features and haphazard trial-and-error construction. LS and TF may have redefined the goal of the task in an effort to regulate and manage the high levels of frustration they were experiencing because of their lack of success. They mentioned, for example, how confident they had been after consulting with their architect friend that they would be able to solve the task in this second session and how disappointed they were that his advice had not worked. Also, in the first session, they explicitly expressed their frustration with the task and with each other twice, but in one instance this emotional event did not produce a shift in their collaborative style and in the other it led to LS becoming an onlooker, still engaged but letting TF try out her idea. In contrast, in the second session their expression of negative affect doubled and in three of the four instances they led to parallel work and to them speculating that the task was really a social psychology experiment on participants' tolerance for frustration. For part of this segment, LS and TF were also off-task and engaged in social conversation, again perhaps as a way to reduce the negative affect produced by their multiple failure experiences.

During the last 4 minutes of the session, LS and TF returned to the goal of building a six-story tower, trying to test individual features of towers systematically. Because they did not mark their re-engagement in the task with an explicit comment, we do not know what led them to return to pursuing the task goal, especially because they continued to discuss whether the task was possible as they built and tested their towers. They did not make much progress, perhaps because the towers and features they tested had already proved unsuccessful in earlier trials.

It is possible that the lack of change in LS's and TF's individual theories from the third theory assessment (i.e., immediately preceding the second collaborative session) and the fourth theory assessment (i.e., immediately following this second collaborative session) was due to their realization that for most of the session, they had been trying to solve a problem (build a stable four or five story tower) that was not equivalent to the experimenter-imposed goal or to the haphazard nature of most of their building making it difficult for them to assess whether the evidence suggested a change in their views.

DV and ST, a Successful Pair

Like LS and TF, DV and ST began their first collaborative session by stating some of the features of their individual theories (DV, no spacing between blocks; and ST, expanded base). Interestingly, DV also brought up a feature that had not been in his initial theory, three-dimensional support. After ST pointed out that only two-dimensional support was needed because the earthquake machine did not move like real earthquakes (i.e., it only moved in one direction and did not have rippling waves), DV abandoned this idea. DV and ST also resembled LS and TF in that they devoted most of their work and discussion to working out a particular feature, in this case, determining whether the spacing between the blocks mattered for tower stability. Their first three towers represented critical tests of the hypothesis that spacing mattered (i.e., they built the first tower with spacing, the second one without spacing, and the third one with spacing). However, after the third tower they decided that because the features of the towers interacted, critical tests of individual features would be of little use. In contrast, while LS and TF questioned the utility of critical tests of individual features of towers, they still returned to the strategy in their second collaborative session.

Table 2. Explanations, analogies, transacts, and scientific methodology used by ST and DV in the first and second collaborative sessions.

DV and ST	Session 1	Session 2
Towers built and tested	14	11
Explanations of building features	6	6
Analogies	3	1
Transacts (critique, elaborate, synthesize)	4	6
Scientific Methodology		
Critical tests of hypotheses	2	1
% Tests evaluate and explain outcomes	42	18

An additional difference between DV and ST and LS and TF concerned their use of explanations, transacts, and analogies. LS's and TF's were interspersed relatively equally during the building and evaluation (i.e., after the test) phases of the session. DV's and ST's, in contrast, were concentrated more heavily during the evaluation phase. It is possible that their more in-depth approach to evaluation was responsible for their greater success in the task; by the end of the first session, DV and ST had built a successful six-story tower. Interestingly, given that the prevalent pattern was for pairs' theories to diverge over time, while DV and ST's initial theories differed, they converged following the collaboration, i.e., in the second relatively individual assessment. Their individual theories still were quite similar (they differed only in one feature) when they returned one week later and received the third relatively individual assessment.

DV and ST began their second collaborative session by reviewing the characteristics of the successful tower they had built in the previous session. They built and tested this tower successfully on their first try and were given four more blocks and the goal of building an eight-story tower that would withstand the simulated earthquake. After receiving this new goal, their discussion shifted from considering the merits of specific features to considering features as interrelated to each other and how these interrelationships might differ in six- versus eight-story towers. As they discussed these interrelations, they tinkered with their original six-story design to adapt it to a successful seven-story tower and subsequently, to an eight-story tower that withstood a 4-second earthquake. An additional change during this session was that their explanations and transacts were no longer concentrated heavily in the evaluation phase; rather, they were more frequent during the building segment. Perhaps this redistribution of transacts and explanations reflects their emphasis on tinkering and refining their design to meet their new goal. Once again, the theories they espoused in their fourth and final relatively individual assessment (i.e., after the second collaborative session) differed only in one feature. However, there were shifts in the strength with which they held particular beliefs. For example, relative to his third relatively individual assessment, ST became more convinced that cross-bracing and absence of spacing were important, and less convinced that an expanded base was necessary. DV's conviction that cross-bracing was important increased from the third to the fourth relatively individual theory assessment and he became more unsure about whether spacing between blocks was desirable. Taken together, these individual and collaborative patterns suggest that DV and ST devoted their first collaborative session to theory building and their second collaborative session to theory refinement.

In contrast to LS and TF, DV and ST did not question the feasibility of solving the task. They also did not explicitly express frustration in either session and their interaction style across trials was smoother, rarely deviating from collaboration. Their confidence in their ability to solve the task may have allowed them to have a smoother and less frustrating interaction, which, in turn, freed more resources to devote to the task. As proposed earlier, it is possible that their decision to abandon critical tests of hypotheses and their tendency to engage in regular post-mortem discussions may have helped them succeed.

Conclusions

Taken together, our findings add to previous research showing that in designing for science, we need to allow for both relatively social and relatively individual moments of work and reflection. In classrooms, laboratories, or research studies we often worry when collaborators disengage and individuals proceed to work on their own. Our preliminary data suggest that these moments are necessary for theory building and revision. However, it is important to distinguish these moments of solitary reflection or emotional regulation from situations that signal that the collaboration has fallen apart and cannot be repaired. Currently, we are continuing to analyze our collaborative sessions to address further the question of when and why people work together during scientific discovery and when they prefer to work alone. Our hope is to link these individual and social rhythms systematically to both affective processes and knowledge states. We are also continuing to try to discern why individuals did not communicate verbally all of the features of their theories. Thus far, we have ruled out the hypotheses that they communicated verbally about features that they were unsure about and its alternative, that they shared ideas they were highly confident about. While we are only in the beginning steps of this work, we hope that it will contribute to our description and explanation of the social context scientific reasoning and discovery.

We close by returning to our opening point that science is situated in historical, cultural, and social contexts. Whether we are examining scientific understanding at a particular time in history, the scientific practices of a culture, or the social discourse in a research group meeting or a classroom, it soon becomes evident that certain knowledge, problems, processes, and solutions are privileged over others. Through participation in scientific activities, children and adults master the valued practices of their communities (Goodnow, 1990; Hatano, 1994; Wertsch, 1997). Mastery of scientific practices can further individuals' cognitive development and provide opportunities for success in a variety occupations. However, these practices can also be constraining because they involve particular ways of conceptualizing reality and exploring causal phenomena (Wertsch, 1997). Shifts in scientific paradigms and perspectives occur when enough members of a community become so dissatisfied with the prevalent theories or methodologies that they seek alternatives (Kuhn, 1964). Often, these alternatives draw on different disciplines. An example of such shift is the current influx of ideas and methodologies from literary theory (e.g., Bakhtin, 1981) into the social and, to an extent, natural sciences that started in the late 1970s when many scholars rejected the positivist tradition.

Although alternatives to the positivist tradition have been created within professional communities, it is still the case that in Western schools, we socialize a way of thinking about and doing science that involves inductive and deductive reasoning and controlled experimentation and hypothesis testing. Whether it is working on a project for a science fair in elementary school and junior high school, carrying out laboratory assignments for physics, chemistry, or psychology courses in high school and college, or designing theses and dissertations, we teach students to follow appropriate procedures for building, testing, and revising their theories about particular domains. As we showed in this chapter, despite this socialization, adults can recognize when the scientific method will not be useful in solving a problem. When they leave the classroom and become professionals or engage in everyday science, people will encounter the ill-formed types of problems that we used in the present research. Thus, we suggest that identifying the nature of the problem—whether or not it is amenable to critical hypothesis testing and has a preferred or ideal solution pathway—should be an important part of training and designing for science.

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