

## Introduction to “New Conceptualizations of Transfer of Learning”

Robert L. Goldstone and Samuel B. Day

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Introduction to “New Conceptualizations of Transfer of Learning”  
*Robert L. Goldstone and Samuel B. Day*

## Introduction to “New Conceptualizations of Transfer of Learning”

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Understanding how to get learners to transfer their knowledge to new situations is a topic of both theoretical and practical importance. Theoretically, it touches on core issues in knowledge representation, analogical reasoning, generalization, embodied cognition, and concept formation. Practically, learning without transfer of what has been learned is almost always unproductive and inefficient. Although schools often measure the efficiency of learning in terms of speed and retention of knowledge, a relatively neglected and subtler component of efficiency is the generality and applicability of the acquired knowledge. This special issue of *Educational Psychologist* collects together new approaches toward understanding and fostering appropriate transfer in learners. Three themes that emerge from the collected articles are (a) the importance of the perspective/stance of the learner for achieving robust transfer, (b) the neglected role of motivation in determining transfer, and (c) the existence of specific, validated techniques for teaching with an eye toward facilitating students’ transfer of their learning.

Most educators want their students to apply what they have learned beyond its original classroom context. Biology teachers want their students to understand the genetic mechanisms underlying heredity, not simply how pea plants look. Physics teachers want their students to understand fundamental laws of physics such as conservation of energy, not simply how a particular spring uncoils when weighted down. Unfortunately, having students transfer what they have learned to new scenarios that draw on the same principles has proven surprisingly difficult to achieve (Detterman, 1993; Gick & Holyoak, 1980, 1983). Considerable research indicates that students often do not spontaneously transfer what they have learned, at least not across superficially dissimilar scenarios. In one striking example, Perkins (2009) cited the amusing, but also horrifying, case of physics students who learned in class how to determine how long it would take a ball to fall to the bottom of a certain height tower (see Figure 1A) and then were given on an exam the problem of determining how long it would take a ball to fall to the bottom of a well (the

scenario on the right). Students complained that they were not given any well problems in class.

However, there are recent suggestions that students can, under some circumstances, transfer their knowledge across superficially dissimilar domains (Pedone, Hummel, & Holyoak, 2001; Schwartz, Bransford, & Sears, 2005; Schwartz, Sears, & Chang, 2007). In fact, in some cases, transfer seems to be spontaneous and automatic. When people are first shown the unambiguous man illustration on the left, they subsequently interpret the ambiguous man-rat figure as a man, but when they are first shown the rat illustration on the right, they interpret the ambiguous picture as a rat (Figure 2; Leeper, 1935). This kind of perceptual priming is not typically construed as transfer, but it does represent a clear case in which people spontaneously carry along acquired interpretational strategies without explicitly trying to apply their learning to new situations.

The goal of this special issue of *Educational Psychologist* is to synthesize new theoretical positions, informed by empirical data, about whether and how transfer of knowledge is achievable. This is a timely topic for *Educational Psychologist* because of the recent resurgence of interest in transfer. Part of the reason for this resurgence is the renewed

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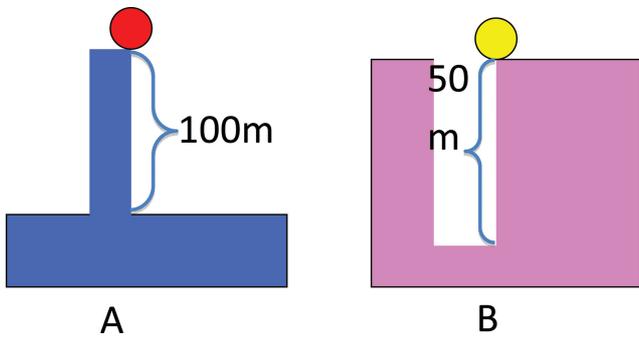


FIGURE 1 A graphic illustration of the challenge of transferring acquired knowledge. Note. David Perkins (2009) reported a physics classroom in which students were first given falling ball problems of the kind illustrated in A. Students were shown how to determine how long it would take the ball at the top of the 100-m tower to reach the ground. They were later tested on problems such as B in which a ball started at the top of a 50-m well and fell down to the bottom. Several students complained that they had never been given “well” problems before, only “tower” problems (color figure available online).

understanding that important principles frequently arise in different domains. For example, complex systems principles such as positive and negative feedback loops arise in economics, geology, physics, chemistry, biology, and the social sciences (Chi & VanLehn, 2012/this issue; Goldstone & Wilensky, 2008). Students who learn about a positive feedback systems from an example of a microphone feeding into, and placed near, a loudspeaker are missing out on an opportunity for applying their knowledge to an economics situation of people purchasing products that other people had already purchased if they do not engage in cross-domain transfer. It is true that there is a major trend in science toward increasingly specialized research topics. However, there is also a scientific movement to reverse this trend, pursuing the possibility that the same principles can describe seemingly very different phenomena. One attractive aspect of this movement from an educational perspective is that it promotes a view of science that is enfranchising rather than alienating. Students who can apply the Diffusion-limited Aggregation principle that they learned while exploring copper sulfate formations

to the growth and structure of cities, lungs, and snowflakes (Ball, 1999) will likely develop an appreciation of science in which any field can potentially bear on another field (Chi, 2005; Chi, Slotta, & deLeeuw, 1994).

Another reason for a renewed interest in transfer in cognitive science and education is that there has been a methodological shift from measuring transfer by learners’ explicit statements of correspondence between domains to implicit, indirect measures that students may be sensitive to the connection between situations without being able to explicitly verbalize the basis for the connection. This expanded view of what counts as evidence for transfer has taken several forms. Some researchers have focused on how students learn how to see events as manifesting principles, and how this learning prepares them for seeing future events in terms of the same principles (Bransford & Schwartz, 1999). Other researchers have looked for indications that students have been influenced by previous activities by examining how they construe situations as similar to the earlier activity (Lobato, 2003, 2012/this issue; Lobato & Seibert, 2002). Similarly, researchers have argued for transfer occurring by students developing perceptual interpretations of an initial situation and simply continuing to use the same interpretational bias when interacting with a second situation (Day & Goldstone, 2011, 2012/this issue; Goldstone, Landy, & Son, 2010).

The specific goals of this special issue are to discuss what we know about transfer of learning and how best to foster it. The contributed articles tackle core questions such as

- How is transfer best conceptualized?
- Is transfer of learning to (apparently) dissimilar situations a viable, and valuable, goal?
- How is transfer affected by the ways in which materials are presented by instructors and approached by students?
- What are the best methods of pedagogical practice for fostering transfer?
- What are the cognitive, distributed, and social processes that underlie transfer?
- What are the roles of context, perception, grounding, rules, and formalisms for achieving transfer?

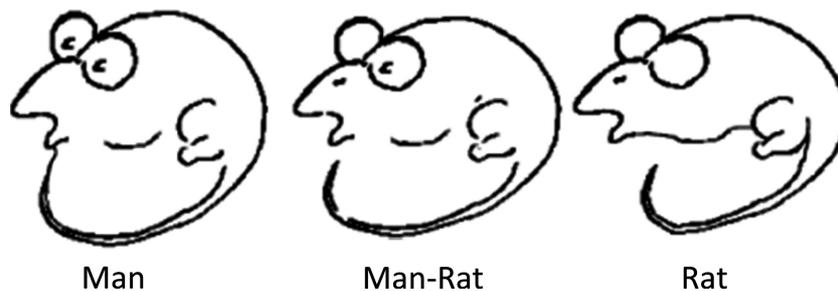


FIGURE 2 Stimuli from Leeper (1935), from “A Study of a Neglected Portion of the Field of Learning—The Development of Sensory Organization,” by R. Leeper, 1935, *The Pedagogical Seminary and Journal of Genetic Psychology*, 46. Note. When the ambiguous man-rat is preceded by the unambiguous man, it is spontaneously interpreted as a man, but when it is preceded by the unambiguous rat, it is spontaneously interpreted as a rat.

## INTEGRATIVE THEMES

As a way of orienting the reader to the articles to follow, we briefly mention three themes that unify the contributions and are likely prospects for fertile future research. A first theme is that the perspective and active learning stance of the learner makes a critical difference for transfer. Whether transfer occurs is not simply a function of the similarity between the original and new situations. It is fundamentally a function of the proclivity of the learner to make a connection between the situations. This theme prominently appears in Lobato's (2012/this issue) "actor-inspired" approach that focuses on what a learner stands to benefit from transferring their previous learning, and Engle, Lam, Meyer, and Nix's (2012/this issue) prescriptions for encouraging students to frame what they are learning in an expansive fashion to foster transfer. Schwartz, Chase, and Bransford (2012/this issue) focused on the need for students to adopt a mind-set in which they are oriented toward adapting, not just applying, their knowledge. For Chi and VanLehn (2012/this issue) and Lobato (2012/this issue), transfer literally involves adopting new perspectives—developing new ways of seeing familiar situations. At a broader level, Richland, Stigler, and Holyoak (2012/this issue) reported evidence indicating that entire cultures differ in the emphases that they place on connecting situations. Sensitivity to individual and cultural differences in the quantity and quality of cross-situational connections will be important for tailoring teaching for transfer and for finding ways to inspire students to be "intellectual entrepreneurs" who proactively create their own opportunities for leveraging their prior knowledge. The approaches described in the following articles collectively indicate that transfer can occur in a diversity of ways when learners are actively involved in interpreting new situations. A greater appreciation of the diversity of transfer may help us to see troubling aspects of positive transfer (Schwartz et al., 2012/this issue) as well as positive aspects of so-called negative transfer (Lobato, 2012/this issue). All too often, negative transfer is shorthand for "transfer in a way that conflicts with what the teacher/experimenter intended." Learners have their own agendas, and understanding these agendas will help us help students apply their previous experiences in a useful and generative manner.

A second theme particularly emphasized in Perkins and Salomon's (2012/this issue) discussion is the need to reconcile the cognitive bases for transfer with motivational considerations. Even if a student possesses ideal cognitive abilities for drawing apt connections among experiences, opportunities for transfer will still be forfeited if the student is not motivated to draw out these connections. Cognitive work is necessary for properly taking in experiences, for transforming these experiences into transportable encodings, and for figuring out how these encodings are applicable to new situations. The issue here is not only how to inspire students to do this cognitive work but how to inspire them to inspire themselves to interpret their world in useful ways. Standard

approaches to transfer from cognitive science have underemphasized the importance of motivation for achieving transfer, and incorporating motivation into cognitive accounts will allow these accounts to better explain successful and unsuccessful cases of transfer (Nokes-Malach & Belenky, in press).

A third theme is that efforts to teach students with an eye toward transfer will incorporate a diverse set of methods aimed at training flexible thinking. Whereas many training programs emphasize "accelerated learning," speed should not be viewed as the only measure of efficiency. The generalization potential for learning is just as important a facet of efficiency, even though far more research on assessment is needed to develop adequate measures of generalization potential. Several specific proposals for training flexibility in thought are presented in the articles that follow: focusing on interactions between surface features (Chi, 2012), invention-based training (Schwartz et al., 2012/this issue), comparison-based training (Richland et al., 2012/this issue), actor-oriented approaches (Lobato, 2012/this issue), taking advantage of well-grounded perception and action processes (Day & Goldstone, 2012/this issue), and explicit framings to encourage developing transportable representations (Engle et al, 2012/this issue). Rote training procedures may achieve efficient learning of specific behaviors, but this is only a short-term goal. The "real" goal is for learners to behave in a thoughtful and adaptive manner. Learning scientists risk falling into exactly the same "failure to generalize" trap that they have documented so well in their experimental subjects if they insist on measuring only the most easily quantified variables of response time and percent correct on problems sampled from the same set as the training problems (D. Schwartz, personal communication, August 5, 2011). Fortunately, the current contributions attest to our collective ability to avoid limited learning from our previous studies and theories by simply switching from one rote procedural training system to another. At our best, we are "learning scientists" in both senses of the phrase—scientists that study learning and scientists that are learning from our predecessors', and our own, mistakes.

## ACKNOWLEDGMENTS

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# The Import of Knowledge Export: Connecting Findings and Theories of Transfer of Learning

Samuel B. Day and Robert L. Goldstone

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*Samuel B. Day and Robert L. Goldstone*

## The Import of Knowledge Export: Connecting Findings and Theories of Transfer of Learning

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After more than 100 years of interest and study, knowledge transfer remains among the most challenging, contentious, and important issues for both psychology and education. In this article, we review and discuss many of the more important ideas and findings from the existing research and attempt to bridge this body of work with the exciting new research directions suggested by the following articles.

Like many of the people reading this article, we find mathematics intrinsically interesting. However, even if most students shared in our appreciation of the inherent elegance of mathematical explanation, it is unlikely that this would justify the immense amount of educational time spent on the topic. The goal of learning mathematics is to prepare students to use it in the real world, or even more broadly, to employ rigorous, formal thought processes to their everyday life. In various ways, the same can be said for any educational topic—from physics to history to biology to literature, education is fundamentally about acquiring knowledge to be used outside of the classroom. It is therefore especially troubling that a considerable corpus of research finds systematic failures in people's ability to apply their relevant knowledge in new situations. Because of both the difficulty and the importance of transfer, aspects that bear on the very foundation of education, an enormous amount of research has been conducted on knowledge transfer. The topic remains both frustrating and contentious; however, with some researchers going so far as to argue that meaningful transfer seldom if ever actually occurs (e.g., Detterman, 1993).

We had two primary goals in writing this article. First, as a lead-in to this special issue, we have attempted to provide a review of the (sometimes daunting) existing literature on knowledge transfer. Of course, such a review will never

be close to complete. However, we have tried as much as possible to include a broad sampling of some of the more important and influential findings and ideas and to organize these along themes that are renewed by the current set of articles. When combined with the other articles in this issue, our hope is to provide the reader with a solid understanding of the “state of the art” in transfer research. Our second goal for this article was to join with the other authors in presenting our own proposal for a productive way of advancing research in this area—namely, a discussion of the role of perceptual processes and perceptual representations in knowledge transfer.

### FINDINGS FROM THE TRADITIONAL APPROACH TO TRANSFER

The traditional approach to knowledge transfer has its roots in ideas from the early 20th century. In particular, Thorndike's (1924; Thorndike & Woodworth, 1901) seminal ideas regarding the importance of overlapping features, or “identical elements,” between the learning and transfer situations remain an important aspect of current psychological theories. However, contemporary views of transfer have been very much shaped by the computational metaphor of cognition that emerged during the “cognitive revolution” of the 1960s (see Gardner, 1987), and much of the psychological research on transfer has become tightly linked with symbolic cognitive approaches, particularly with theories

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65 of analogical reasoning (e.g., Gentner, 1983; Hummel & Holyoak, 1997, 2003). It is therefore worth spending some time reviewing some of the assumptions of these approaches.

70 According to traditional cognitive approaches, knowledge is represented in terms of systems of discrete symbols, each of which corresponds to a meaningful concept (see Markman, 1999). To meaningfully represent a situation, these mental symbols are combined according to a structured syntax that defines the relationships between the constituent concepts. As an example of the critical role that relations play in knowledge representation, the situation described by the sentence “John loves Mary” reflects a different set of relationships than the situation described by “Mary loves John,” although both are made up of the same three constituent symbols (*John*, *Mary*, and *loves*). This capacity to productively reconfigure the same set of symbols into many distinct structures is one of the primary benefits of the symbolic approach, and it provides a very straightforward way of capturing the power of the human cognitive system (Fodor & Pylyshyn, 1988).

85 These assumptions, that concepts are represented in a way that is psychologically discrete and allows for flexible recombination, have important consequences for cognition. Most important for our purposes, they imply that the *structure* of a situation may be understood and processed independently of the particular objects and features that are involved. For example, consider the following situation: *John loves Mary, but Mary loves David, causing John to be jealous of David*. The symbolic approach allows us to easily generate new situations involving a completely new cast of characters while maintaining the same underlying system of relationships—for example, *Susan loves Mark, but Mark loves Gretchen, causing Susan to be jealous of Gretchen*. Furthermore, this approach allows for the possibility of understanding the system of relations independent of *any* specific characters, that is, holding an abstract representation of a “love triangle.”

100 According to traditional cognitive approaches, it is this capacity to represent systems of relations independently of the objects and features that they bind together, which underlies our ability to reason analogically (see Gentner, 1983). An analogy is simply a match between the systems of relations in two represented situations (their “deep structure”), regardless of any differences in the objects and features they involve (their “surface features”). An individual’s recognition of this similarity relies on a mapping process, in which structurally based correspondences between the situations are identified (e.g., in the aforementioned examples, John and Susan would correspond to each other as a result of their shared role of “jealous unrequited lover”). This mapping process may then support *analogical inference*, the generation of some new potential knowledge on the basis of these structural commonalities. For example, when confronted with a situation in which Nick loves Melanie but Melanie loves Greg, one might use prior knowledge to reasonably conclude that Nick will be jealous of Greg.

120 Traditional approaches to knowledge transfer fundamentally rely on this symbolic conception of analogical processing. For example, a student may learn a formula for mathematical permutations in the context of a problem involving pizza toppings (e.g., Ross, 1984), and subsequently encounter a new permutations problem that describes the assignment of people to teams. To effectively make use of the information from the first problem, the student must recognize the structural commonalities between the two cases, despite their overt surface differences, and use his or her understanding of the correspondences to correctly assign values to the variables in the formula. Although there is some variation in the theoretical approaches taken by different researchers (e.g., Gentner, 1983; Hummel & Holyoak, 2003; Keane, Ledgeway, & Duff, 1994), psychologists have widely adopted the view that transfer is the recruitment of previously known, structured symbolic representations in the service of understanding and making inferences about new, structurally similar cases. 125 130 135

### Surface Similarity

140 Over the last several decades, the traditional view of transfer has been a fertile source of research and has greatly expanded our understanding of the conditions under which transfer is likely (and unlikely) to occur. By far the most robust finding involves the influence of the concrete surface similarities between cases. Although psychologists view structural similarity as the critical component in meaningful, productive knowledge transfer, research has repeatedly shown that it is the surface commonalities between cases that are more often the driving force in determining whether transfer actually occurs (e.g., Anderson, Farrell, & Sauters, 1984; Holyoak & Koh, 1987; Reed, 1987; Ross, 1987; Salomon & Perkins, 1989; Singley & Anderson, 1989). When a new case differs in its surface characteristics from a previously learned analogous case, spontaneous transfer is typically quite poor (e.g., Gick & Holyoak, 1980, 1982; Simon & Hayes, 1976; Weisberg, DiCamillo, & Phillips, 1978). 145 150 155 Q2

In general, the greatest cognitive difficulty seems to be in simply noticing that a new case is structurally similar to a previously known one. For instance, Gentner, Ratterman, and Forbus (1993) found that although structural commonalities predicted the degree to which participants found an analogy to be “apt” or inferentially sound, these abstract similarities were very unlikely to produce reminding on their own. In contrast, surface commonalities between two cases led to frequent reminders, even though participants explicitly recognized their limited benefit. 160 165

Probably the best known (and most cited and replicated) example of this type of recognition failure is the work of Gick and Holyoak (1980, 1983), based on Duncker’s (1945) classic “radiation problem.” In that problem, individuals are told about a patient with an inoperable tumor in his stomach. There is a kind of ray that could be used to treat the 170

change "will" to "would"

175 patient, but at intensities sufficient to destroy the tumor, a  
great deal of healthy tissue would also be destroyed. At lower  
intensities, the ray would be harmless to healthy tissue but  
will not affect the tumor. Individuals are asked to propose  
a solution that could destroy the tumor while also leaving  
healthy tissue intact. The intended solution involves a con-  
vergence approach, in which several low intensity rays are  
180 administered from different locations but converge at the site  
of the tumor, creating a greater aggregate intensity there.  
Participants have a very difficult time solving this problem  
independently. Furthermore, preceding the problem with a  
relevant analogous example—for instance, a story about sol-  
185 diers simultaneously converging on a fortress—did little to  
improve performance (Gick & Holyoak, 1980, 1983). How-  
ever, when the demands for spontaneous reminding were re-  
moved from the task by giving participants an explicit cue to  
consider the relevance of a previously learned situation (e.g.,  
190 “the story you read earlier might be relevant in solving this  
problem”), transfer rates were dramatically higher (also see  
Catrambone & Holyoak, 1989; Reed, Dempster & Ettinger,  
1985).

195 In the absence of such hints, however, recognition fail-  
ures can be surprisingly robust. In one striking example,  
Anolli, Antonietti, Crisafulli, and Cantoia (2001) interrupted  
participants during their attempts to solve Duncker’s radi-  
ation problem, asked them to answer a relevant question  
about the previously seen, analogous problem, and then al-  
200 lowed them to continue working on the test problem. Despite  
this seemingly extreme manipulation, successful transfer oc-  
curred only rarely (5–10% of the time) and was no better than  
a control condition in which no analogous prior problem had  
been given.

205 As previously discussed, in the symbolic view of analog-  
ical processing, reminding is only the first step in achieving  
transfer. To make accurate inferences between the cases, af-  
ter reminding occurs individuals must perform a mapping  
between the two representations to determine structural cor-  
210 respondences. There is evidence that surface similarity can  
have an important influence during this phase as well. High  
surface similarity between entities in the same role (e.g., en-  
tities that would be represented by the same variable in a  
mathematical formula) tends to facilitate transfer, even when  
215 reminding is not a factor (Ross, 1987, 1989). This can be  
contrasted with cases of “cross-mapping,” in which two sit-  
uations share similar entities, but these entities play *differ-*  
*ent* roles within their respective systems. For example, after  
studying a problem in which various cars are assigned to  
220 mechanics, an individual may be asked to solve a new prob-  
lem in which mechanics are assigned to cars. Under these  
conditions, the concrete commonalities between the situa-  
tions may improve reminding (Ross, 1989), but the added  
difficulty required in *ignoring* the surface similarities be-  
225 tween entities during the mapping process (because *cars* in  
the study problem does not correspond to *cars* in the trans-  
fer problem) generally leads to poorer overall performance

than when cross-mapping does not occur (Gentner & Toupin,  
1986; Ross, 1987, 1989).

230 In general, however, more attention has been given to the  
role of surface content on reminding than on mapping, and,  
in fact, these kinds of effects may be seen as an example  
of the broader influence of encoding specificity (Tulving &  
Thomson, 1973) on memory and knowledge application. In-  
235 deed, Barnett and Ceci (2002) have developed a fairly com-  
prehensive taxonomy of the many ways in which learning  
and transfer situations may differ from one another. These  
included factors such as physical context, temporal context,  
functional context, social context and modality, in addition  
240 to the content of the materials themselves. The authors sug-  
gested several areas for future research to fill gaps in our  
knowledge about the effects and interactions between these  
factors, but also noted many existing studies in which differ-  
ences along these dimensions negatively influenced transfer.  
245 For instance, Spencer and Weisberg (1986, again using a ver-  
sion of Duncker’s radiation problem) found that even small  
changes in the context of the learning and testing episodes  
(one was described as an experiment, the other as a classroom  
exercise) eliminated all evidence of transfer, even though the  
250 physical context (the classroom) remained constant and the  
delay between tasks was only a few minutes.

255 Likewise, there is evidence that the similarity between  
the kinds of cognitive processing used during learning and  
testing may influence the likelihood of transfer. For instance,  
researchers have examined people’s ability to solve brief in-  
260 sight puzzles, such as, “A man in the U.S. married 20 dif-  
ferent women in the same town. All of them are still living  
and he has never divorced one of them, yet he has broken  
no law. Can you explain?” Surprisingly, providing partici-  
pants with highly relevant information immediately prior to  
265 the test phase (e.g., reading the sentence “A minister marries  
several people each week.”) has no impact on their ability to  
correctly solve the problems (Perfetto, Bransford, & Franks,  
1983). However, when this prior information is presented in  
a way that mirrors the likely “confusion-resolution” process-  
270 ing involved in the test puzzles—such as, “You can marry  
several people each week . . . if you are minister”—transfer  
rates increase considerably (Adams et al., 1988; Lockhart,  
Lamon, & Gick, 1988).

275 The literature thus provides a strong and consistent picture  
of the role of similarity in transfer. Structural similarity repre-  
sents the actual basis for meaningful knowledge transfer, and  
people are aware of, and sensitive to, this fact (e.g., Gentner  
et al., 1993). In practice, however, contextual similarity be-  
tween the situations themselves seems to play a much larger  
280 role in determining whether transfer will actually occur.

### Discerning Deep Structure

The role of surface similarity in transfer represents a very  
serious issue for educators. Educational curricula contain an  
enormous number of concepts that students are expected to

master, each of which reflects (directly or indirectly) some knowledge or skill that is presumed to be of value outside of the classroom. The literature on similarity and transfer suggests that students may often fail to recognize the relevance of these ideas when they are confronted with analogous situations in the real world, particularly when the specific concrete details of those situations do not closely match those presented by teachers. However, the sheer breadth and volume of the material to be learned, combined with limited class time, means that this will typically not be the case. Teachers will never be able to anticipate and address most of the contexts in which important concepts could be applicable. Furthermore, even if this were possible, research suggests that students would encounter difficulties simply because of changes to the learning context itself: Information learned in the classroom is often unlikely to be accessed and applied outside of the classroom (e.g., Spencer & Weisberg, 1986). Findings such as these seem to call into question the entire enterprise of formal education.

However, the research discussed earlier also points to some reasons for hope. Researchers found that when information was encoded in a way that made it more accessible during the test phase—for instance, by matching the kinds of cognitive processes that were likely to be engaged (Adams et al., 1988; Lockhart et al., 1988)—transfer was much more likely to occur. More broadly, there has been a considerable amount of research looking at the ways in which specific aspects of the mental representations that learners initially form may help (or hinder) their ability to generalize their knowledge in new contexts.

Most frequently, these efforts have involved seeking ways to emphasize the structural aspects of the learned representations while deemphasizing contextual features that are irrelevant to that structure. Sometimes this has been accomplished very directly. For instance, after giving children a story to read, Ann Brown and her colleagues (A. L. Brown, Kane, & Echols, 1986) asked them a few questions emphasizing relevant aspects of its underlying goal structure, such as the protagonist, the goal, and the obstacle to be overcome. Under these conditions, children were more than 3 times as likely to spontaneously suggest the relevant strategy when solving a new problem. The researchers also found that the children who had emphasized these structural aspects of the story on their own, without the leading questions, were similarly quite likely to transfer the solution (also see Gick & Holyoak, 1983).

Another straightforward way to emphasize structural features during learning is through explicit labeling. For example, Catrambone (1996, 1998) found that labeling the subgoals involved in a complex mathematical procedure helped students accurately understand the important structural aspects of a new problem, and thereby transfer the solution more effectively. This result held even when the label was not inherently meaningful. Labeling has proven particularly effective in research with younger children (e.g., Kotovsky

& Gentner, 1996; Loewenstein & Gentner, 2005). For instance, preschool-aged children were better able to recognize and take advantage of structural commonalities between two physical models when the spatial locations of one of the models were meaningfully labeled (e.g., *in*, *on*, *under*; Loewenstein & Gentner, 2005). For adults as well, labels that emphasize structural relations can promote transfer to new situations that are structurally similar (Son, Doumas, & Goldstone, 2010).

Perhaps the most obvious way of deemphasizing the superficial, context-specific aspects of a situation is by simply reducing their presence in the training materials. Evidence suggests that this can also be an effective strategy. For instance, the “seductive details” effect (e.g., Garner, Gillingham, & White, 1989) occurs in situations where interesting but structurally irrelevant information distracts learners from the important concepts to be acquired. Harp and Mayer (1997) found that recall and transfer from a scientific passage dropped precipitously when interesting but tangential text or illustrations were included (also see Garner, Brown, Sanders, & Menke, 1992; Garner et al., 1989; Hidi & Baird, 1988; Wade, 1992). Similarly, Mayer, Griffith, Jurkowitz, and Rothman (2008) reported studies in which interesting extraneous information significantly impaired transfer while leaving retention largely intact. Based on these results, the authors argued that even if the added extraneous material is engaging, the net benefit for learning may be negative due to interference with the deep cognitive processing necessary for the construction of generalizable knowledge structures.

The presence of completely extraneous information seems to represent a clear impediment to learning and transfer. A potentially more insidious issue, however, involves contextual content that is inherently relevant to the training materials. For instance, an instructor may present the concept of *positive feedback systems* through a specific contextualized example, such as the effects of polar melting on global warming. In this case, the concrete details of the situation—the sun, the ice, the reflected light—may still interfere with a learner’s ability to transfer their knowledge to new contexts, even though they promote comprehension of the example. Researchers have had some success in facilitating mapping and transfer between situations by simply reducing the “richness” of the content in the training materials (e.g., Clement, Mawby, & Giles, 1994; DeLoache, 1995; Goldstone, Medin, & Gentner, 1991; Goldstone & Sakamoto, 2003; Markman & Gentner, 1993; Rattermann & Gentner, 1998). For example, Goldstone and Sakamoto (2003) taught participants about the principle of *competitive specialization* in the context of ants foraging for food. When a computer simulation of the system portrayed these ants as dots rather than realistic drawings, participants were better able to transfer their knowledge to a new, superficially dissimilar instantiation of the same principle. Clement and colleagues (1994) found a similar pattern with text materials that used domain-general or domain-specific words. For instance, a domain-general version of one of the

scenarios described a political candidate who *stole* ideas and *incorporated* them into his speeches; in the domain-specific version, the candidate was described as *plagiarizing* ideas and *typing* them into his speeches, terms which are much more specific in their applicability. Participants in these studies were far more likely to recognize and retrieve structurally similar cases when their relationships were described in more domain-general rather than domain-specific terms.

In work with young children, DeLoache (e.g., 1991, 1995; DeLoache & Burns, 1994) has consistently found evidence that salient concrete details in a learning experience can impair knowledge transfer, even between situations that are seemingly very similar. In one of her standard experimental paradigms, children watch a miniature item being hidden in a small model of a room (e.g., a miniature toy might be hidden under a miniature bed) and are then asked to find the matching item in the corresponding location of a matching full-sized room (a real toy under a real bed). Younger children have a surprisingly difficult time with this task. However, their success or failure can be influenced by the subjective concreteness of the learning case. For instance, they are more successful when the initial model is a two-dimensional image rather than a three-dimensional scaled model. Similarly, it was found that children were better able to transfer their knowledge from a scaled model when it was seen behind

insert comma before "but" ~~do~~ but transfer was impaired when they were allowed to interact and play with the scaled items prior to using the model to find the corresponding items in the full-sized room. DeLoache argued that these effects reflect the difficulty of representing something both as a physical object and as a symbol for something else and that this issue is exacerbated when the concrete physicality of the object is emphasized.

As some of these examples demonstrate, the notion of concreteness is not necessarily equivalent to the objective "quantity" of perceptual features. Perhaps the broadest and most applicable way of construing concreteness is in terms of the amount of information that a representation conveys to a particular individual (e.g., Kaminski & Sloutsky, in press). For instance, a simple line drawing of a cat would contain less information than a photograph of a cat, and would therefore be a less concrete representation. Important to note, this conception of concreteness can reflect more than just the information inherent to the materials themselves. For instance, a picture of one's *own* cat could be considered even more concrete, in that it evokes a great deal of previously existing knowledge. Along these lines, Kaminski, Sloutsky, and Heckler (2008) taught students about the *modulo* 3 operation, using either symbols representing a familiar, well-structured context (e.g., line drawings of measuring cups) or more generic symbols without any relevant preexisting associations. The generic symbols led to much greater transfer to a new context, whereas performance by the concrete training group did not differ from chance. Similarly, Son and Goldstone (2009) reported that participants' ability to transfer the

principles of signal detection theory was impaired when the protagonist of the scenario was a well-known fictional television character rather than an anonymous doctor. Activation of specific, preexisting knowledge appears to have negative consequences for transfer similar to the hindrance for transfer caused by overt contextual detail.

There is therefore a broad range of evidence that reducing the concrete content of a learning experience can aid in an individual's ability to apply their knowledge to new, dissimilar situations. Taken to its natural conclusion, this pattern suggests that the ideal learning materials would be those that eliminate such information altogether. For instance, mathematical ideas could be taught entirely in terms of numbers, variables, and formulae, or a principle such as "positive feedback loop" could be conveyed in terms of abstract relationships and processes (e.g., "A system in which changes to a variable result in additional changes to that variable in the same direction"). However, evidence suggests that this is generally an ineffective approach. Although completely abstract materials can present information in a way that is both efficient and maximally general, it seems to do so at the expense of comprehensibility (e.g., Bruner, 1966; Carraher, Carraher, & Schliemann, 1987; see Nathan, 2012, for a related argument).

In one clear example of the issues associated with complete abstraction, researchers (LeFevre & Dixon, 1986) provided participants with both explicit written instructions for a task and a worked example. For some participants, however, these two sources of instruction were in conflict and reflected entirely different tasks that would lead to different correct responses. Under these conditions, more than 90% of the participants ignored the verbal instructions and instead followed the example of the worked concrete problem. Work by Ross (1987) suggests a similar phenomenon. In his study, participants learned about a particular mathematical procedure in the context of a specific, concrete example. During a later test, individuals were provided with the correct formula needed to solve a new analogous problem. Nevertheless, performance was significantly affected by the details of the example that had been seen earlier (also see Anderson et al., 1984). A similar pattern has been observed in perceptual classification tasks. Even when people know a simple, clear-cut rule for a classification, performance is better on frequently presented, compared to rare, examples (Allen & Brooks, 1991).

A recent study by McNeil and her colleagues (McNeil, Uttal, Jarvin, & Sternberg, 2009) captures the complexity of the issue of concreteness in learning. Students in that study were less successful in solving word problems about money when the task involved interaction with actual physical bills and coins than when it did not. However, the concreteness of the physical money seemed to convey some important advantages as well. Analysis of students' work showed that those who used the perceptually rich money were less likely to make conceptual errors (i.e., they were

more likely to attempt the correct mathematical operations), suggesting that the concreteness helped them to comprehend the overall structure of scenarios. Similarly, in a recent study exploring the tradeoffs between contextually grounded versus abstract (equation-based) representations, Koedinger, Alibali, and Nathan (2008) found that for simple problems, grounded word problems were solved better, but for complex problems, equations were solved more accurately. In both of these studies, the real-world contextualization provides useful checks and constraints that prevent certain kinds of mistakes, but this same contextualization can interfere with transfer to new, complex situations.

### Combining Concreteness and Abstraction

The research on concreteness in learning and transfer presents researchers with some confounding issues. On one hand, presenting information via concrete examples may lead to mental representations that are overly “bound” to a particular context and may interfere with a person’s ability both to recognize new situations where their knowledge could be relevant and to apply their knowledge in an appropriate way. On the other hand, efforts to circumvent these problems by presenting information abstractly, with minimal specific context, may seriously impair the learner’s ability to accurately represent the information at all. Educators may, reasonably, feel faced with the unappealing task of choosing between comprehensibility and applicability.

Of course, these extremes do not represent the only possibilities, and researchers have given serious attention to finding ways to leverage the benefits of both concreteness and abstraction. For instance, Goldstone and Son (1995) conducted a study in which a previously unfamiliar scientific principle (competitive specialization) was taught through two interactive computer simulations, each of which could be either relatively concrete or relatively idealized. They found that participants showed superior performance on learning and transfer after interacting with one concrete and one idealized version of the simulation, relative to participants who had interacted with two simulations of the same type. This advantage was especially pronounced under conditions of “concreteness fading,” in which a concrete simulation was followed by one that was less perceptually rich. Scheiter, Gergets, and Shuh (2010) replicated and extended this finding. In their study, a computer simulation demonstrated a continuous morphing between very concrete and more abstract visual representations. For example, an initial display of realistically rendered trees became progressively less detailed, until they were ultimately transformed into small green squares, which were then combined into larger contiguous groupings that made the relative proportions of different types of trees very salient. This approach (which simultaneously used both rich and idealized representations and facilitated cognitive mapping between the two types) led to reliable gains in transfer.

One of the most investigated—and apparently most effective—ways of overcoming the limitations of specific concrete examples is by comparing multiple dissimilar cases. This approach can allow a learner to encode the content in terms of meaningful, comprehensible situations, but then to distill the structurally relevant information on the basis of commonalities across the examples. In particular, there is evidence that the act of mapping the correspondences between two situations (i.e., identifying which entities play the same respective roles) can serve to highlight the structural content. For example, Loewenstein, Thompson, and Gentner (2003) conducted research with management (MBA) students enrolled in a course on negotiation. Some of the students compared two specific cases involving a “contingency contract,” a useful but sometimes counterintuitive negotiation technique. Other students received the same two cases but read and analyzed them sequentially, without any explicit comparison. Later, all students took part in a face-to-face bargaining exercise in which the use of a contingency contract represented the optimal approach. Students who had compared cases were nearly 3 times as likely to apply this principle to the new case as those who had analyzed the cases separately. In fact, the latter group performed no better on the transfer task than those who had received no training on the contingency principle at all. Results from many other studies across a variety of contexts are consistent with the idea that comparison and mapping between dissimilar cases facilitates structural processing (e.g., Catrambone & Holyoak, 1989; Christie & Gentner, 2010; Cummins, 1992; Gentner, Loewenstein, Thompson, & Forbus, 2009; Gick & Holyoak, 1983; Richland & McDonough, 2009). In one example from a real-world educational setting, Richland and McDonough (2009) found that explicitly cuing the meaningful commonalities between two math problems—for example, by visually presenting both examples at once and gesturing between corresponding aspects of them—improved students’ ability to transfer to new cross-mapped cases.

Research on this approach has typically involved explicit, directed comparison between cases, but there is also evidence that multiple examples may provide a benefit under less directed conditions as well. Quilici and Mayer (2002) taught students about statistical tests (*t* test, chi-square, correlation) by sequentially presenting a set of examples that systematically varied surface and structural properties. Specifically, students read examples describing *t* tests in three different concrete contexts, followed by examples of chi-square tests in the *same* three contexts, followed by the same for correlation problems. Although participants in this study were not explicitly asked to map between the cases, the structure of the problem presentation invited at least informal comparison. Consistent with this, transfer rates were reliably higher relative to other study structures.

Ross and Kennedy (1990) also examined the effects of nondirected comparison. Specifically, when participants in their study used a previous example to solve a new problem

Is "scientific passage" supposed to be singular or plural? Add "a" before "scientific" if singular. Add "s" after "passage" of plural.

add "s" to "comparison" to make plural because "analogies" is plural.

(as a result of spontaneous reminding), they then showed superior performance on *subsequent* problems of that type. This is consistent with the idea that the initial reminding and application involved a comparison and mapping process that helped to create a stronger structural representation. The authors suggest that this kind of “unsupervised” comparison reflects a natural and realistic way in which generalizable knowledge could develop in the real world, particularly given that in many domains, surface, and structural characteristics tend to be correlated (e.g., Gentner, 1989; Lewis & Anderson, 1985; Mayer, 1981). Finally, as discussed earlier, research has found that explicit labeling can be beneficial in highlighting structural commonalities between situations (e.g., Catrambone, 1998). Some researchers have argued that these labels are effective because they invite spontaneous comparison (e.g., Kotovsky & Gentner, 1996; Namy & Gentner, 2002), and there is some recent evidence to support this interpretation (Son et al., 2010).

Despite a growing body of evidence for the benefits of comparison, however, the results are not uniformly positive. For example, Reed (1989) found that comparing two algebra problems did not improve performance on new problems. Catrambone and Holyoak (1989) found that although comparison helped transfer in the short term, these benefits disappeared after short delays or changes in context (although longer term transfer could be facilitated through more intensive, experimenter-directed comparisons). In one recent study (Mayer, DeLeeuw, & Ayres, 2007), exposure to multiple cases was actually found to impair transfer. Participants in that study learned about the design and function of hydraulic brake systems, and some of those participants also saw descriptions of other types of brake systems (air and caliper brakes). The researchers found that those who had learned about multiple systems performed worse on tests of both retention and transfer than those who had only learned about one. One possible explanation for this disadvantage is that the transfer questions in this study all involved inferences about hydraulic brakes themselves, not inferences based on any structural commonalities across the different systems. If true, this suggests that the benefits of generalizability associated with comparison may sometimes come at the expense of more specific kinds of knowledge.

Overall, however, research suggests that the comparison of multiple cases represents a particularly promising avenue for developing generalizable representations from concrete examples. There are still important questions about the optimal ways of organizing these comparisons, however, and much less evidence exists regarding the kinds of cases that should be compared. On one hand, a case could be made that comparing situations with very dissimilar surface features should lead to the best generalization. If comparison serves to highlight commonalities between cases while deemphasizing differences, comparing situations that share irrelevant features could result in those features being retained in a learner’s mental representation (the idea of “conservative generaliza-

tion”; Medin & Ross, 1989; Ross & Kennedy, 1990). This, in turn, could limit generalizability to new, dissimilar cases. Some research is consistent with this conclusion (e.g., Day, Goldstone, & Hills, 2010; Goldstone & Sakamoto, 2003; Halpern, Hansen, & Riefer, 1990; Rittle-Johnson & Star, 2009). For example, Halpern and colleagues (Halpern et al., 1990) asked students to read scientific passage that included either “near” (superficially similar) or “far” (superficially dissimilar) analogies. The passages including far analogies led to superior retention, inference, and transfer than those featuring superficially similar comparison, which showed no benefit at all.

On the other hand, there are also good reasons to suggest that the comparison of more similar cases might be beneficial, particularly early in the learning process. As discussed earlier, the process of mapping two representations to find structural correspondences is facilitated when entities in similar roles are concretely similar. The less similar two situations are overall, the less likely it becomes that corresponding entities will share overt surface similarities, and thus the process of mapping itself becomes both more cognitively demanding and more prone to error (see Gentner, Loewenstein, & Hung, 2007). Together with the considerable evidence that cognitive demands represent a general impediment to learning (see Sweller, 1999), this suggests that there may be circumstances in which the comparison of concretely similar cases would lead to better transfer, and there is some evidence to support this idea. For instance, Kotovsky and Gentner (1996) found that although young children initially had a very difficult time recognizing and responding on the basis of structural similarities between perceptually dissimilar stimuli, they became reliably better at this task when they had first observed the structural commonality between overtly similar stimuli, a phenomenon termed “progressive alignment” (also see Gentner et al., 2007; Loewenstein & Gentner, 2001).

Thus, there is some evidence for each of these two competing ideas—that transfer will benefit most from the comparison of similar and of dissimilar cases. One possible way to reconcile these findings is by suggesting that different kinds of learners may benefit from different kinds of comparisons. In the absence of other constraints, comparisons of dissimilar situations should be best, because they can serve to highlight only those features that are relevant to the broadest possible set of applicable cases. Of course, learning and cognition are inevitably subject to (often serious) constraints. When an individual’s working memory capacity is more restricted, because of limited background knowledge, individual differences in ability, or both, the comparison of concretely similar cases may be preferable. In fact, some recent findings are consistent with this idea (Day, Hills, & Goldstone, 2010; Rittle-Johnson, Star, & Durkin, 2009). If this reconciliation is correct, then a general recommendation for promoting transfer would be to present a principle using the most dissimilar cases that still allow a learner to compare the cases and recognize the basis for their similarity.

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### Prior Knowledge

Several lines of research have established that an individual's existing knowledge can provide a significant advantage in his or her ability to recognize and take advantage of deep structural content. One of the classic findings in this area comes from the work of Chi, Feltovich, and Glaser (1981) examining the differences between experts and nonexperts in the domain of physics. The researchers found that experts (advanced physics PhD students) overwhelmingly tended to group physics problems on the basis of the general principles underlying their solution (e.g., conservation of energy, Newton's second law). In contrast, relative novices (undergraduates who had just completed an introductory mechanics course) were much more likely to group problems by their concrete features (e.g., the presence of springs, inclined planes, pulleys, etc.). This general pattern, with experts using meaningful structural commonalities to assess similarity and novices using surface features, has been replicated in a wide range of domains. For instance, expert programmers tend to sort computer programs on the basis of their underlying algorithms, whereas novices are more likely to sort on the basis of application type (Weiser & Shertz, 1983). Similarly, trained musicians were found to group musical pieces exclusively by similarities in their melodic and harmonic structure, whereas nonmusicians had a strong bias to group them by similarities in instrumentation (Wolpert, 1990). Likewise, when expert and novice subjects were asked to solve the Tower of Hanoi puzzle and judge the similarity between the goal and various states, experts' judgments were more likely to be based on the number of moves required to transform one position to the other, rather than number of shared superficial features (Suzuki, Ohnishi, & Shigemasa, 1992). Although most of this research has examined individuals that are already experts in their field, similar effects can be induced experimentally through training. For example, Schoenfeld and Hermann (1983) found that students were more likely to sort mathematical problems on the basis of their underlying structure after an intensive training course on mathematical problem solving.

Important for our purposes, these expertise differences appear to have a strong influence on the likelihood of spontaneous analogical reminding and use. For example, Novick (1988) found that students with greater expertise in mathematics (as assessed by scores on the mathematical section of the SAT) were much more likely to make use of previously seen problems that were analogous but overtly dissimilar to a new test problem. In contrast, the nonexpert students were more likely to be influenced (negatively) by reminders of prior problems with surface commonalities (also see Ball, Ormerod, & Morley, 2004; Gentner et al., 2009).

Of course, experts are not completely immune to the influence of surface features (e.g., Blessing & Ross, 1996; Hardiman, Dufresne, & Mestre, 1989). In fact, in some circumstances, experts' greater knowledge and experience can

leave them susceptible to new kinds of surface influences. For instance, Blessing and Ross (1996) asked experienced math students to solve story problems that varied in both their surface features (the cover story of the problem) and their underlying structure (the formula necessary to solve them correctly). According to prior research, one might predict that these experts would have learned simply to ignore the irrelevant contextual information and focus solely on the abstract relationships within each problem. However, these students' prior experience had provided them with additional relevant information: that certain kinds of mathematical problems tend to be presented in certain kinds of contexts. The researchers found that students' performance was impaired when the problems involved content that was typically associated with a different type of solution formula (also see Bassok, Wu, & Olseth, 1995; Hinsley, Hayes, & Simon, 1978).

Overall, however, expertise provides significant advantages for transfer. There are many factors that might contribute to this fact. Experts may have simply had more practice construing situations in terms of the abstractions that are relevant to their field. For instance, physicists are likely to be quite good at thinking about specific problems in terms of abstract objects and forces. Because of this, their mental representations of two problems that involve the same underlying principles are likely to be fairly similar, which would facilitate both reminding and mapping. One of the most important factors in experts' transfer, as we discuss in the next section, is that their rich background knowledge allows them to overcome limitations in working memory.

### Cognitive Load and Task Difficulty

Potentially the greatest constraint on learning in general, and therefore on transfer, is the severe cognitive restriction on the amount of information that can be processed at any one time. Research on working memory (see Baddeley, 2000; Baddeley & Hitch, 1974) has provided a wealth of evidence that individuals are only capable of keeping a handful of units of information active simultaneously and are able to actively manipulate even fewer. Furthermore, this kind of knowledge is typically very short-lived. In the absence of active rehearsal, information tends to remain active for only a few seconds.

These facts are especially relevant for transfer because there are reasons to suspect that structural knowledge in particular could be disproportionately influenced by such restrictions. In general, learners need to represent the individual entities in a situation before they are able to represent the relationships between those constituent parts (e.g., Goldstone & Medin, 1994). This suggests that when an individual has limited resources to devote to a set of facts—perhaps because new content in a lecture is displacing it quickly—it is the representation of the relational structure that is most likely to suffer (see Halford, Wilson, & Phillips,

825 1998). Similarly, this limited capacity means that learners  
 have fewer opportunities to elaborate on the new information  
 by generating new inferences, making connections to exist-  
 ing knowledge, and developing more general schemas from  
 the information (e.g., Sweller, 1994). Given this, limitations  
 830 in cognitive capacity could lead to serious difficulties in both  
 recognizing and making use of analogous structures.

There is empirical evidence to support this idea. Waltz  
 and colleagues (Waltz, Lau, Grewal, & Holyoak, 2000) ex-  
 amined people’s ability to recognize structural commonalities  
 835 between pairs of visual scenes, each of which portrayed vari-  
 ous people and objects interacting in some way. For example,  
 one picture showed a woman receiving groceries from a man  
 from a food bank, while the paired picture showed the same  
 woman giving food to a squirrel (see Figure 1). In this and all  
 840 of the pairs, one of the entities was “cross-mapped” between  
 the images—for example, the woman in the first picture cor-  
 responded to the woman in second picture on the basis of

their similar physical appearance, but she corresponded to  
 the squirrel in terms of their shared role as “recipient of  
 food” (see Markman & Gentner, 1993). The question of inter- 845  
 est was which of these alternatives participants would select  
 when asked which entity corresponded to the first woman.  
 Under normal conditions, the relational match (the squirrel)  
 and the perceptual match (the woman) were chosen about  
 equally often. However, when participants were put under 850  
 a cognitive load during the task—for example, by asking  
 them to maintain a string of digits in memory—they were far  
 more likely to ignore the structural features and prefer the  
 perceptually similar match. Similar results have been found  
 from manipulations that deplete working memory capacity 855  
 indirectly, such as inducing anxiety in participants (Tohill &  
 Holyoak, 2000).

Because of the critical role that working memory con-  
 straints play in learning and transfer, researchers have been  
 very interested in determining effective ways of managing 860

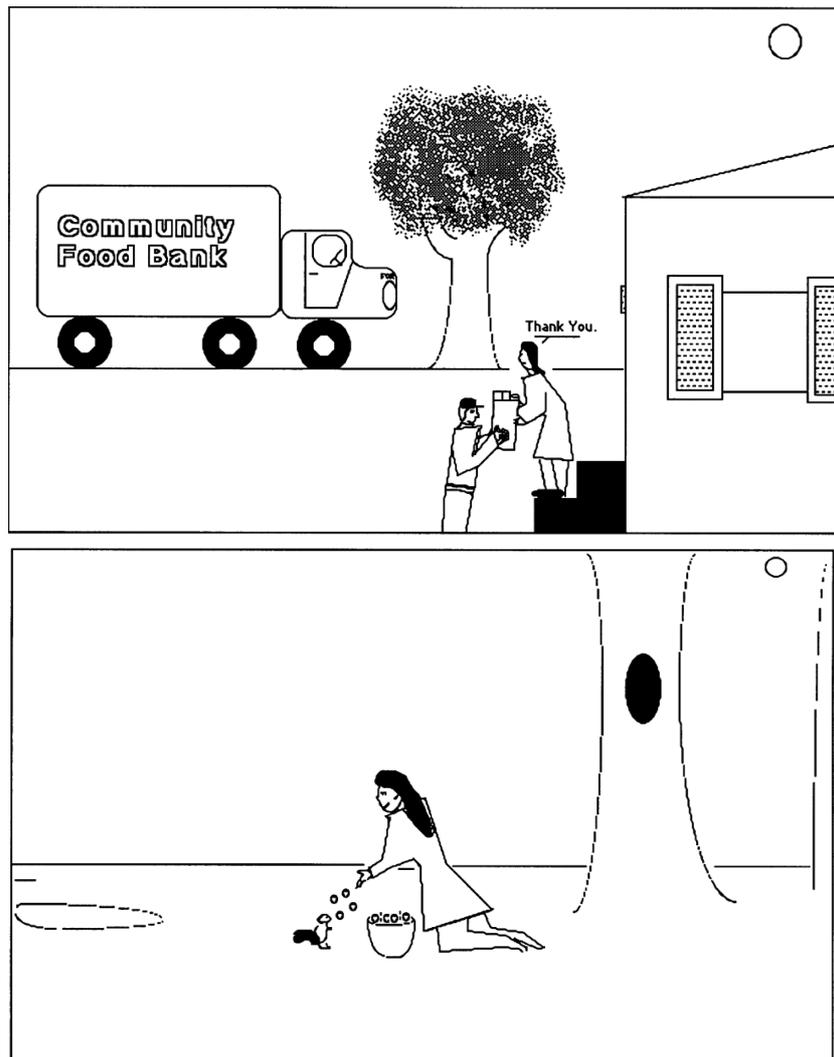


FIGURE 1 Sample stimuli from Markman and Gentner (1993) used by Waltz et al (2000).

delete "the" and change "removal" to "removing" to keep verb consistency since all the other examples begin with verbs.

processing demands during learning. *Cognitive load theory* (CLT; Sweller, van Merriënboer, & Paas, 1998), which distinguishes between different kinds of cognitive demands based on their relevance to learning, has provided a productive framework for examining these issues. For example, several studies have reported superior learning and transfer after students had been shown several worked examples (see Renkl, 2005; Renkl & Atkinson, 2010). This *worked-example effect* is typically explained in terms of learners having the opportunity to develop meaningful schemas without having unnecessary demands placed on their cognitive processing. Other research has shown that learning can benefit from manipulations such as the removal of irrelevant, distracting content (e.g., Garner et al., 1989), using cues to direct attention to relevant content (e.g., Lorch, 1989; Mautone & Mayer, 2001), allowing learners to pace their own training in order allow sufficient processing time (e.g., Lusk et al., 2009; Mayer & Chandler, 2001), and “pretraining” students on relevant sub-components of a system prior to the complete training phase (e.g., Mayer, Mathias, & Wetzell, 2002; Pollock, Chandler, & Sweller, 2002).

CLT also takes into consideration the constraints of auditory and visual working memory. These constraints are independent (e.g., Baddeley, 1986) and are not subject to a heavy processing demand from auditory or verbal content) that can interfere with processing for visual content (e.g., visual content). Because of these constraints, it is more difficult to more effectively balance the demands of these two subsystems. For instance, several studies in which the presentation of visual material that was accompanied by oral narration led to better learning and transfer than the simultaneous presentation of visual material and text (e.g., Mayer & Moreno, 1998; Moreno & Mayer, 1999; Moreno, Mayer, Spires, & Lester, 2001). In this case, presenting the visual and verbal content in different modalities avoids overloading a single system. Other studies have found benefits associated with aligning images and text spatially (e.g., Hegarty & Just, 1989; Moreno & Mayer, 1999) and synchronizing their presentation temporally (e.g., Mayer & Anderson, 1991, 1992; Mayer & Sims, 1994), both of which should reduce the length of time that information must be maintained in working memory.

In all of these examples, the degree to which learners’ working memory is taxed has an important influence on their ability to acquire new knowledge, and particularly their ability to develop knowledge structures that can generalize to new situations. In fact, constraints on cognitive processing almost certainly play a role in many of the transfer effects that have already been discussed. For example, both the facilitation observed in analogical mapping between similar objects and the impairment associated with “cross-mapping” entities to dissimilar roles (e.g., Gentner & Toupin, 1986; Ross, 1987, 1989) are likely to reflect the relative difficulty of maintaining similar versus dissimilar correspondences in

working memory. Likewise, the labeling of relational structures (e.g., Catrambone, 1996, 1998) may be beneficial in part because it serves to reduce cognitive demands by grouping and thereby simplifying the information to be stored and processed.

One of the clearest examples of the role of processing constraints on transfer is in the differences between experts and novices. Specifically, expertise seems to involve specialized kinds of processes and representations that allow an individual to efficiently work around these severe cognitive constraints. A considerable amount of evidence supports the idea that proficiency in a content domain is not associated with improved storage or processing capacity per se. Rather, individuals are able to become much more *efficient* at processing information through the acquisition of long-term knowledge structures. Through the process of *chunking*, experts may reduce very large quantities of information into a much smaller number of representational units. For instance, although a novice looking at a chessboard in mid-game is confronted with an overwhelming amount of information, chess experts are able to quickly recognize and classify large groups of pieces into a small number of meaningful structures (e.g., Chase & Simon, 1973; de Groot, 1966). Important for our purposes, chunked knowledge structures such as these not only allow individuals to encode content far more quickly and remember configurations much more effectively. They also serve as a kind of classification which enables experts to associate appropriate procedures and strategies with different kinds of complex situations. For example, a physics expert may classify diverse problems into structurally meaningful categories (e.g., Chi et al., 1981) that highlight relevant relationships and suggest specific kinds of solutions.

Although there are many clear examples of benefits from reducing the cognitive demand associated with learning, the story is made somewhat more complex seemingly contradictory evidence for the benefits of cognitive difficulty. “Desirable difficulties” (Bjork, 1994) are aspects of a learning situation that make immediate learning and encoding more difficult but that also enhance long-term retention and retrieval. Although such effects have typically been examined in terms of basic information recall, several studies suggest that certain kinds of difficulties during training may enhance transfer as well. For instance, Kornell and Bjork (2008) showed participants several examples of paintings from each of 12 different artists and then looked at the participants’ ability to generalize their knowledge by recognizing new paintings by those artists. Participants overwhelmingly preferred conditions in which the paintings by any particular artist were grouped together consecutively, and believed that this presentation improved their test performance. In reality, however, the more challenging “spaced” presentation, in which paintings by each artist were presented “interleaved” with those of other painters, led to reliably better generalization.

In a more typical problem-solving transfer test, Chen and Mo (2004) found that although greater variability in training

add "do" before "not"; otherwise, there is more of an expectation of finding a "but also" in the same sentence.

insert "by the" before "seemingly"

975 examples led to slower, more difficult learning, it also left participants better equipped to generalize their knowledge to new transfer problems. Similarly, researchers have found that participants' ability to transfer a solution to an insight problem was improved when the source problem was presented in a way that made structural relationships within the problem *less* salient, and therefore more difficult to encode (Didierjean & Nogry, 2004; Gick & McGarry, 1992). In all of these cases, the introduction of difficulty during training improved later transfer performance.

980 The recommendations from CLT and Desirable Difficulties are, on the face of it, conflicting, and each has its share of empirical support. One possible reconciliation of these conflicting results is that introducing difficulties into learning can confer benefits for transfer so long as solid learning is nonetheless achieved. Reminiscent of Nietzsche's aphorism "What does not destroy me, makes me strong," the recommendation would be to introduce learning challenges that do not completely derail learning. Adaptive learning technologies that adjust the difficulties of materials while learning is ongoing represent a promising way of implementing this recommendation.

### Types of Processing and Strategic Approaches

995 All of the effects discussed thus far have related to influences outside of the learner's immediate control—features inherent in the learning materials and situations themselves, or knowledge that individuals bring from their prior experience. However, transfer can also be affected by a variety of online factors, reflecting different kinds of processing used during encoding or transfer.

1000 Surprisingly little evidence exists regarding one of the most direct potential processing influences—namely, whether individuals can be in a cognitive state that causes them to interpret things more or less relationally in general. In one of the few studies on this question (Bliznashki & Kokinov, 2010), researchers recently reported evidence that engaging in one task that requires relational construal of information can prime participants to interpret subsequent situations more relationally. Specifically, after attempting several items from the Raven Progressive Matrices test, which involves solving visual analogies based on structural relationships between a series of diagrams, participants were more likely to judge the similarities between new scenes based on structural rather than featural information. Relatedly, in research with young children, A. L. Brown and Kane (1988) found that 3- and 4-year-old participants seemed to "learn to learn," quickly developing a mind-set to look for relational similarities between cases after previous exposure to other analogous situations. However, much work remains to be done on this fundamental issue.

1020 Another way in which learners may influence their own encoding is in terms of the specific goals with which they approach a given task. A great deal of research over the

past two decades has examined the influence of achievement goals on learning, primarily in terms of *mastery* versus *performance* goals (see Ames, 1992). Although mastery goals relate to basic competence, with the aim of personal learning and improvement, performance goals relate to success on the immediate task, particularly in terms of demonstrating one's ability relative to others. These competing goal types have been shown to have a significant impact on learning in general (see Elliot, 1999; Pintrich, 2000), with mastery goals being associated with greater engagement and long-term success, as well as correlating well with a variety of factors beneficial to learning, such as persistence and the adoption of appropriate cognitive strategies. Recent research has revealed similar effects on knowledge transfer more specifically. For instance, Bereby-Meyer, Moran, and Unger-Aviram (2004) put groups of participants into a negotiation task and examined their ability to maximize their gains through the use of mutually beneficial strategies. Some participants were given instructions that emphasized immediate performance and the minimization of errors, whereas others received instructions that emphasized content mastery. All participants' performance improved on subsequent versions of similar tasks. However, when participants transferred their knowledge to a new scenario in which important conditions and details were changed, those in the performance-oriented condition performed no better than a control group, whereas those who had been given mastery-oriented instructions improved reliably. Other research has extended this finding to situations in which such achievement orientations were primed at the time of transfer rather than during initial learning (Bereby-Meyer & Kaplan, 2005). Similar results have been found by simply varying the specificity of learners' goals during training (Vollmeyer, Burns, & Holyoak, 1996). When participants in that study were provided with a specific goal to achieve in the training phase, immediate performance was good. However, transfer to a task with a new goal was reliably poorer than for participants who had freely explored during training without any specific goal.

Finally, there is evidence that individuals may vary greatly in the quantity and quality of explanations that they spontaneously generate when studying examples and that these differences can have an important influence on their ability to learn and transfer from studied materials. Influential research by Chi and colleagues (Chi, Bassok, Lewis, Reimann, & Glaser, 1989) found that students who self-explained well—explaining and justifying steps in an example problem, and considering goals, consequences, and the relationships between subsequent actions—were far more successful at solving later transfer problems. Renkl (1997) replicated and expanded on these findings, reporting large effects of self-explanation even when controlling for time on task, and distinguishing between several qualitatively different types of explanation styles, which he found to be quite stable within individuals across situations. This *self-explanation effect* seems to benefit learning via multiple routes, both by

1080 supplementing the presented information through the gener-  
ation of relevant inferences and by helping learners to recog-  
nize and correct disparities between their own mental models  
and the ones suggested by the examples (see Chi, 2000).

1085 Following on these correlational results, researchers have  
had some success in improving transfer by eliciting self-  
explanations from learners, particularly in combination with  
other favorable learning conditions. For instance, Renkl,  
Stark, Gruber, and Mandl (1998) used multiple worked ex-  
amples to teach participants about compound interest calcula-  
1090 tion and found that participants who had been trained to  
generate appropriate self-explanations (through the observa-  
tion of good self-explanation, followed by practice with feed-  
back and coaching) exhibited reliably better transfer perfor-  
mance. In another study (Atkinson, Renkl, & Merrill, 2003),  
1095 researchers found that transfer following training through a  
“fading” procedure, in which worked-out steps were succes-  
sively removed from training examples, was improved when  
participants were prompted for self-explanations at each step  
of the training problems.

### Challenges to the Traditional View

1100 Although the traditional approach to transfer has generated  
an enormous body of research, it has also come under an  
increasing amount of criticism. Many of the basic themes of  
this criticism are captured by the influential work of Lave  
(1988), who lays out several interrelated points of concern.  
1105 Most fundamentally, she questions the model of knowledge  
representation that underlies (explicitly or implicitly) the basic  
cognitivist approach. Traditional psychological research  
tends to view knowledge as a stable mental entity, which under  
the right conditions may be brought forth and applied to  
1110 new situations. For example, a student may learn a general  
rule for applying the distributive property to a mathematical  
formula. When confronted with a problem in which this  
method would be appropriate, the student may retrieve this  
existing knowledge structure and apply it to the new problem.  
1115 Although there are many ways in which this process  
could break down—a failure to successfully retrieve the exist-  
ing knowledge, an inaccurate mapping between the known  
method and the new situation—the relevant knowledge itself  
is typically treated as a discrete, reified entity. In fact, the  
1120 very word “transfer” seems to reflect this assumption—that  
a discrete piece of knowledge is being “carried over” intact  
from one context to another.

Q11 Lave presented a very different view of knowledge, both  
in terms of acquisition and use. In this view, all knowledge  
1125 is a by-product of participation in particular situations and is  
very much tied to those specific contexts. Because of this, the  
most traditional kind of knowledge transfer between dissimilar  
cases is simply not possible, because there is no knowledge  
that is in a sufficiently abstracted form to be applicable  
1130 across highly variable contexts. Rather, new knowledge is  
constructed in the course of understanding and participating

in new situations, a process generally referred to as “situated  
learning.” (As Greeno, 1997, p. 12, noted, however, Lave  
does not explicitly say that far transfer cannot occur, but that  
there are serious concerns about the underlying theory on 1135  
which this assumption is based.)

Q12 In particular, Lave and colleagues emphasized the social  
and interactive nature of learning, observing that learning  
typically takes place in “communities of practice,” or groups  
of people who interact in the service of shared interests and 1140  
goals. For example, when Lave and Wenger (1991) analyzed 1143  
the process of learning within several different communities  
of shared interest (e.g., Yucatan midwives, apprentice tailors,  
members of Alcoholics Anonymous), they found a general  
pattern in which newcomers to a group gradually acquired 1145  
knowledge from more experienced members as an incidental  
by-product of group participation. Apprentice tailors, for  
instance, typically begin their careers by performing a number  
of seemingly trivial tasks—running errands, preparing the  
1150 tailor’s materials and workspace at the beginning of each  
day, adding finishing details to garments that the tailor has  
completed—that serve to familiarize the novice with the  
framework of fundamental knowledge of that community.  
The apprentice’s responsibilities gradually progress “back-  
ward” to cutting and sewing jobs, and this progress “can be 1155  
arranged and interrelated in ways that gradually transform  
that skeletal understanding” (p. 96).

In addition to questioning the established views of what  
constitutes learning, Lave also took issue with many practical  
aspects of the experimental research on transfer. For 1160  
instance, transfer research is typically designed to measure  
participants’ application of one particular principle or strategy,  
which is chosen or designed by experts whose knowledge  
may be quite different from that of the learners. In so doing,  
most transfer studies prioritize expert knowledge while over- 1165  
looking or disregarding the relationships that novice partici-  
pants find relevant. As an example, Lave cited a study  
(Williamson, Hollan, & Stevens, 1983) that describes an indi- 1170  
vidual attempting to understand and make predictions about  
a heat exchange mechanism (a system in which cool fluids  
are used to reduce the temperature of hotter fluids). Over the  
course of answering questions about this system, the individ-  
ual generated multiple, distinct models of its operation. New  
questions allowed the learner to recognize flaws in his previ-  
ous models, and in trying to integrate and coordinate these 1175  
different models he both improved his models and furthered  
his overall understanding of the system. Lave argued that tra-  
ditional studies of learning and transfer that are based solely  
on matches to experimenter-generated “normative” models  
and solutions would have failed to capture this individual’s 1180  
learning and knowledge.

Lave also noted that the r design for assessing transfer in  
artificially constructed examples is not representative of  
that example’s influence on a single subsequent case (which 1185  
has been judged analogous by an expert). This “two-problem”

insert comma  
before "he"

design seems to severely restrict the scope of what prior knowledge a participant can meaningfully bring to bear on a new situation.

1190 These critiques have resonated with many researchers interested in learning and education and have been adapted and expanded upon in various ways, both in terms of theory and application. For example, Carreher and Schliemann (2002) argued that the idea of transfer itself represents a theory rather than an actual phenomenon to be investigated or explained. Furthermore, they believe it is a theory that is largely incompatible with existing empirical findings, and one which should therefore be abandoned. In reviewing the literature, and in their own studies examining fifth-grade students' acquisition of the concept of negative numbers, they found little evidence for any of the passive "carrying over" of knowledge between cases that the transfer metaphor implies. Instead, in-depth interviews with their student participants suggested that they were "drawing upon a broad history of experience regarding numbers, general arithmetical operations, money, notation and diagrams, and so forth" (p. 19), and integrating and adapting that diverse knowledge during the online processes of comprehension and learning. Thus, they argued that existing knowledge is often altered to accommodate new information. Schwartz, Chase, and Bransford (2012/*this issue*) describe this process as seeing the new in the old—interpreting previous situations in new ways. In contrast, traditional views of knowledge transfer seem to allow only the assimilation of new information into static existing knowledge structures—seeing the old in the new.

1215 Other researchers are more open to the value of traditional transfer research, while still agreeing with many of Lave's specific concerns. Lobato and her colleagues (e.g., Lobato, 2012/*this issue*; Lobato & Seibert, 2002) have done work addressing two of the major issues raised by Lave—the emphasis in transfer research on conforming to expert knowledge, and the reliance on simple "two problem" transfer designs. In her work, Lobato has performed in-depth analyses of verbal protocols collected from students over the course of several days of training. Through these analyses, she has been able to identify ways in which students' understandings during training are reflected and adapted during later transfer episodes. In this way, her research allows a much richer picture of what information is being drawn upon during application, and also highlights how that knowledge may develop gradually throughout learning experiences.

1230 In one example (Lobato & Seibert, 2002), a student was observed and interviewed while learning about slope, ratios, and proportionality. In analyzing those protocols, the researchers found evidence that an approach discovered by the student in an earlier session (partitioning a particular rise/run "unit," which could then be iterated any number of times) was brought to bear on a later problem in a very different context. However, this use did not appear to reflect a straightforward importing of a previous piece of knowledge. Rather, the interview suggested an extended process that re-

quired both a reinterpretation of the new problem and an adaptation of the original knowledge.

James Greeno and his colleagues (e.g., Greeno, Smith, & Moore, 1993) offered a reconceptualization of transfer that is related to, but somewhat distinct from, Lave's. Greeno interpreted transfer on the basis of the *affordances* (Gibson, 1977) that a situation offers—in other words, the ways in which an agent may meaningfully interact with a situation. When similar affordances are shared across different situations, there is a possibility for transfer to occur.

As an example, Greeno examined Judd's (1908; replicated by Hendrickson & Schroeder, 1941) classic study in which participants practiced hitting an underwater target with a dart or an air rifle. Some of those participants received an explanation of light refraction and how it could lead to deceptive perceptions of the target's location. Although all participants performed equally well on the initial task, those who had received the additional instruction performed much better on a transfer task in which the depth of the target was changed. Greeno suggested that success on this task depends on attending to the affordances of the situation that are invariant across the contexts—namely, the relative angle of the apparent path of the projectile after hitting the water—rather than attending to any of the other means of adjusting one's aim that would not be invariant across contexts. According to this interpretation, those participants who had received information about refraction were more attuned to the relevant, task-invariant affordances, and thus more likely to interact with the modified version appropriately.

As this example highlights, for Greeno these affordances do not reflect a quality of the external situation itself, but rather a relationship between the situation and the agent who is acting upon it. Greeno argued that just as the idea of motion reflects a relationship between an object and a point of reference, so too does cognition necessarily depend on a relationship between an agent and a context. It is therefore incorrect to treat context as simply an influence on cognition—by his interpretation, the very idea of cognition without context is meaningless.

One of the most influential reconsiderations of learning and transfer is through the idea of *preparation for future learning* (e.g., Bransford & Schwartz, 1999; Schwartz & Martin, 2004). Several decades ago, educational philosopher Harry Broudy (1977) suggested three different ways in which knowledge could be manifested in an individual: replicative knowledge ("knowing that" something is true), applicative knowledge ("knowing how" to accomplish some task), and interpretive knowledge ("knowing with" some existing knowledge). Although traditional tests of transfer have looked extensively at the first two ways of understanding, they have largely ignored the third—the ways in which our prior experience shapes our *interpretations* of new information (see Schwartz, Bransford, & Sears, 2005). Through this kind of application, specific prior knowledge serves as a *lens* for the construal of new content rather than being the

direct *focus* of cognition itself. Consistent with the themes of recent transfer critiques, research has demonstrated powerful interpretive effects of knowledge that would have been overlooked by more conventional measures. For instance, most transfer studies involve a simple manipulation during the study phase (e.g., viewing a relevant analog vs. viewing an unrelated control example), followed by an assessment of this manipulation's effect on a transfer task (e.g., solving a problem). In contrast, Schwartz and Martin (2004) designed a "double-transfer paradigm," in which some participants received additional training between the study and test phases.

In one of their studies, ninth-grade algebra students learned about standardized scores, which allow comparison of individual values across groups with different averages and variabilities (e.g., how does one performance on the high jump compare to another performance on the long jump?). One group of students began by attempting to invent a way of standardizing scores on their own, whereas another group was shown an intuitive way of visually understanding standardization, which they then practiced themselves. The researchers found no difference between the groups in terms of direct transfer to transfer problems given immediately after the manipulation. Typically, this would be interpreted to mean that the manipulation had no effect. However, the study involved an additional manipulation: Prior to testing, half of the students in each group were given additional training on the conventional method of calculating standardized scores. It is important to note that this training was identical for the two conditions. The researchers found that for these students, the initial condition *did* influence transfer performance. Specifically, those students who began by trying to invent their own procedure and *then* received more formal training performed markedly better than the other three groups, whose performance was essentially identical. Apparently, the initial manipulation influenced the way in which individuals were able to *learn* from the supplemental training.

In general, mainstream psychologists have not responded to (or even acknowledged) the critiques from education researchers. In the most prominent direct response, Anderson, Reder, and Simon (1996, 1997) disputed the general claims of situated learning on empirical grounds, pointing to evidence that transfer is possible even across situations that are concretely very dissimilar. Others have complained that the arguments presented by Lave and others are largely untestable and unfalsifiable. However, some of the research and ideas from mainstream psychologists are at least consistent with the points raised by situated thinkers.

For instance, many transfer researchers have discussed an adaptation or "re-representation" phase in transfer, during which one or both of the representations involved is altered to make analogical mapping more consistent (e.g., Clement, 1988; Gentner & Colhoun, 2010; Holyoak, Novick, & Melz, 1994; Keane, 1996). For example, when Clement (1988) analyzed protocols collected during physics problem solving, he found that individuals often transformed or modified prior

cases in order to make them applicable to new problems. Furthermore, he reported that problem solving often involved the generation of *Gedanken* experiments, or novel, artificially constructed thought experiments. Such mental constructions would clearly not involve transferring knowledge from a specific prior case but would instead require learners to draw on and adapt multiple sources of experience.

Consistent with this last point, several studies have examined transfer from "real-world" episodes outside of any experimental context, helping to address issues with the standard "two problem" design. For example, Dunbar (2001) used an "in vivo" approach, in which he recorded weekly meetings from biology laboratories. In analyzing these discussions, he discovered numerous examples of scientists drawing on outside analogies to help them formulate new theories, design experiments, and explain new ideas to one another (also see Ball et al., 2004; Bearman, Ball, & Ormerod, 2007; Christensen & Schunn, 2007). Other research has looked at individuals' ability to retrieve autobiographical examples that are structurally similar to new experimentally presented cases. For instance, Chen, Mo, and Honomichl (2004) found evidence that people were likely to spontaneously retrieve and use relevant folk tales in order to solve new analogous problems. Similarly, Gentner et al. (2009) found that just as comparison of multiple cases can improve transfer to new situations, it can also facilitate retrieval of previously known, structurally similar episodes, including autobiographical memories from an individual's own past.

Traditional cognitive approaches have generally considered analogical reasoning to be a very active, deliberative process in which two situations are explicitly mapped to one another. This characterization is difficult to reconcile with arguments for the importance of "knowing with," or using prior knowledge as an interpretive lens for understanding new situations. However, there is some evidence for less deliberative, more implicit forms of analogical transfer. For instance, Schunn and Dunbar (1996) presented participants with a simulated biochemistry problem that required a strategy of *inhibition* in order to be solved (other participants were given a problem with a different solution strategy). On a molecular genetics problem the following day, these participants were better able to generate the correct inhibition-based solution. Despite this transfer, however, the participants appeared to be unaware of the relationship between the two problems and did not mention the earlier simulation in their verbal protocols or in a questionnaire given after the transfer task. Other recent studies have reported similar effects, even when participants were explicitly asked about the relationship between the training and transfer tasks (e.g., Day & Gentner, 2007; Day & Goldstone, 2011; also see Gross & Greene, 2007). Kostic and colleagues (Kostic, Cleary, Severin, & Miller, 2010) found further evidence for this phenomenon, showing a dissociation between familiarity and recall for previously seen analogical relationships. Participants in that study often knew that they had seen a structurally similar example

1410 earlier in the session, even when they could not explicitly remember the content of that example. This further suggests the likelihood of situations in which the structure of prior experiences may influence later processing without requiring explicit analogical mapping between specific cases.

1415 The critiques of the traditional view of transfer present serious challenges to mainstream transfer research. By pointing out potential problems with the models on which such research is based, such critiques seem to call into question the very foundations and justification for this extensive body of literature, not to mention its findings. On the other hand, it is often not clear to psychologists how these criticisms can be addressed within a straightforward experimental framework.

1420 Contemporary researchers are making progress in bridging this apparent divide, however. The work on preparation for future learning and Lobato’s approach of iterating explicit manipulations with in-depth qualitative analysis provide prime examples of taking these issues seriously while simultaneously maintaining scientific rigor. And as discussed earlier, research by mainstream psychologists is increasingly producing findings that bear on these issues, whether or not that is their explicit goal. The extent to which the critiques of Lave and others will ever be satisfactorily addressed is of course an open question, but examples such as these provide reason for optimism.

### PERCEPTION, COGNITION, AND TRANSFER

1435 Taken as a whole, a review of the literature on transfer provides a story of challenges and frustrations, but also reasons for hope. In one way or another, each of the articles in this special issue draws creatively on broad swaths of this literature—including recent critiques—in order to advance our understanding of how we can best foster generalizable knowledge. In this section, we would like to propose our own suggestion for reconceptualizing transfer, which is, ironically enough, to shift transfer from an abstract, high-level conceptualization to perception–action processes. Specifically, we believe the evidence suggests that perceptual learning and perceptual processes provide a critical foundation for both knowledge representation and knowledge use, and that we can leverage this fact in order to facilitate learning and transfer.

1450 This proposed connection is by no means new. For instance, in their seminal work on expertise and problem solving, Chase and Simon (1973) asserted that “it is no mistake of language for the chess master to say that he ‘sees’ the right move; and it is for good reason that students of complex problem solving are interested in perceptual processes” (p. 387). Later in his career, Herb Simon (2000) maintained that “an audience of scientists will very likely agree that thinking doesn’t always (or maybe not even usually) use the medium of words,” and that often, “seeing is the most efficient way of reasoning” (pp. 119–120). This idea has also intrigued

education researchers. For instance, the views of J. S. Brown, Collins, and Duguid (1989) on situated cognition assume a primary role for perception in knowledge acquisition and use. However, both the interest and the empirical evidence for a relationship between perception and cognition have been expanding rapidly in recent years, and a more thorough consideration seems warranted. There are at least two productive ways in which one can draw connections between perception and cognition. The first, weaker connection is in the terms of the general *kinds* of characteristics that are typically associated with each type of processing; the second, stronger potential connection is the suggestion that cognition may rely on perceptual processes and representations in a very literal way.

1475 Relative to most views of how cognition operates, perceptual processes tend to be very fast, to occur automatically without conscious deliberation, and to rely largely on pattern-matching with respect to existing representations. This, of course, is not to say that perception is either simple or content-free. In fact, the efficiency and subjective ease of perceptual experience belies both the complexity and the flexibility of the processes involved. Some of this efficiency may derive from the availability of general, possibly innate organizing principles, such as those suggested by the Gestaltists (e.g., Metzger, 1936; Wertheimer, 1923) or more recently by developmental psychologists such as Spelke (1990) and Bailargeon (1987). However, perception is also strongly influenced by prior experience. For instance, expertise in a given domain is often accompanied by a kind of perceptual “tuning” that leaves the individual more sensitive to perceptual features and patterns that are relevant to their field (see Gauthier, Tarr, & Bub, 2009). Such gradual adaptation is consistent with other kinds of “non deliberate” learning, such as the acquisition of procedural knowledge and automaticity (e.g., Shiffrin & Schneider, 1977). However, lasting changes in perceptual interpretations can also result from much briefer experiences. A classic example of this is the “rat-man demonstration” (Leeper, 1935), in which a single, brief exposure to an image strongly biases one’s subsequent interpretation of a similar, ambiguous figure (see Figure 2). Similarly, DeSchepper and Treisman (1996) found that a single exposure to an abstract figure influenced individuals’ perception for several weeks, even when they demonstrated no conscious recognition for that figure. In one dramatic demonstration of this type of effect, individuals exhibited facilitated recognition for picture fragments after a single, brief exposure during an initial study conducted 17 years earlier (Mitchell, 2006). Participants in the follow-up experiment frequently reported having no memory for the previous study itself, much less for the specific items.

1505 There are clear parallels between these kinds of perceptual effects and the idea of “knowing with,” in which prior perceptual knowledge is used to interpret new situations. In fact, one recent study (Day & Gentner, 2007) represents a fairly straightforward replication of the rat-man demonstration

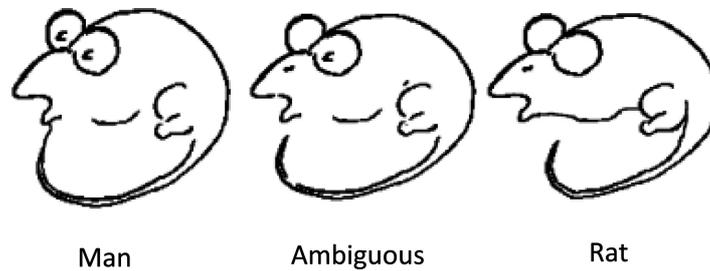


FIGURE 2 The “rat-man” demonstration, from “A Study of a Neglected Portion of the Field of Learning—The Development of Sensory Organization,” by R. Leeper, 1935, *The Pedagogical Seminary and Journal of Genetic Psychology*, 46. Interpretation of the ambiguous figure in the middle is strongly influenced by which unambiguous version the individual has seen previously.

Q20  
Q21

with conceptual materials (narrative passages). In this study, participants’ interpretations of an ambiguous passage were strongly influenced by an unambiguous analogous passage they had recently read, with two different versions of the first passage leading to two different interpretations of the subsequent passage. As in the perceptual task, the structure of a recent stimulus served to guide the interpretation of a new case, although in this instance it was conceptual, relational structure that was being affected. Also paralleling the rat-man demonstration, this influence did not appear to be deliberate or effortful. When participants were asked afterward, they reported that the ambiguous target passage had been completely understandable on its own and that they had not referred to any prior passages in trying to understand the new one. As in the perceptual task, participants in this study not only were unaware of the influence of the first stimulus on the second but also appeared to be unaware of the ambiguity in the second case altogether. Consistent with the concept of *knowing with*, the earlier scenario was not an explicit focus of attention but rather provided a framework through which new incoming information could be structured (also see Day & Goldstone, 2011, discussed next).

However, there are reasons to suggest an even stronger, more direct connection between perceptual and conceptual processes. Specifically, we would suggest that a considerable amount of cognitive activity—even those aspects which seems relatively “abstract”—relies on mental representations that are perceptually and spatially concrete. As such, the relationship between our conceptual and perceptual processes and representations could be considered a very literal one. For example, individuals are reliably faster when responding to smaller numbers with their left hands and to larger numbers with their right hands, a phenomenon known as the “SNARC” effect (Dehaene, Bossini, & Giraux, 1993). Follow-ups and extensions to this study strongly suggest that these individuals are relying on a spatial mental representation such as a number line when performing the seemingly abstract task of assessing magnitude.

Some of the most extensive evidence for the role of perceptual representations in cognition comes from research on mental models. Such models provide a simplified spatial and

mechanical representation of a situation, allowing individuals to reason about relationships within a system and about consequences of different possible actions. In a recent review, Hegarty (2004) discussed a considerable body of evidence supporting the use of such analog spatial models in a variety of mechanical reasoning tasks. For instance, the ability to solve simple mechanical problems is highly correlated with independent measures of spatial ability but not measures of verbal ability (e.g., Hegarty & Sims, 1994). Similarly, such problems experience more disruptive interference from a simultaneous secondary task that involves visuospatial working memory than from one involving verbal working memory (e.g., Sims & Hegarty, 1997). Studies have also found patterns of reaction times for such problems that are consistent with reliance on an analog mental simulation (e.g., Schwartz & Black, 1996). Such phenomena are not limited to mechanical problem solving situations, of course. For instance, research on text processing has repeatedly found evidence for the construction of mental “situation models” in the course of comprehending text passages (see Zwaan & Radvansky, 1998). Through the use of such models, readers are able to quickly and automatically infer the physical affordances of the entities described in text (e.g., Glenberg & Robertson, 2000). In fact, there is evidence that reading comprehension may actually be fostered by asking individuals to “act out” written passages with physical objects (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004).

Mental models can also play an important role beyond such literal approximations of real-world situations. Individuals may also use models that are only analogically or metaphorically similar to novel cases. For example, Gentner and Gentner (1983) reported that learners were very likely to understand concepts related to electrical currents in terms of mental models of flowing water or moving crowds of people. Similarly, Johnson-Laird and colleagues have reported extensive evidence that seemingly very abstract types of logical reasoning are often performed through the use of analog, perceptually-concrete mental representations (see Johnson-Laird, 2006).

The role of perceptual representations in comprehension and reasoning suggests that such content may be important

in transfer as well, and there is a growing body of evidence that this is the case. Some of the earliest evidence involved problems that were inherently and literally spatial in nature. For instance, Dreistadt (1969) reported that individuals were better able to solve a spatial insight problem (e.g., “organize 10 items into five rows of exactly 4 items each”) when a perceptual image that was relevant to the solution (e.g., a star) was present as an incidental feature of the environment. The author reported anecdotally that participants were largely unaware of this influence on their reasoning. In an even earlier example, Maier (1931) reported that participants were much more likely to solve the “two-string” insight problem after witnessing the researcher “accidentally” brush against one of the strings and cause it to swing (a crucial component of the solution). Again, this influence was reported to occur largely outside of conscious awareness.

Recently, we (Day & Goldstone, 2011) examined the possibility of achieving “far” transfer through similar means. Specifically, we hypothesized that because knowledge transfer appears to be contingent on the psychological (rather than objective) similarity between two situations, and because individuals often seem to represent complex situations through simplified, concrete mental models, it is possible that transfer could occur between cases that appear quite dissimilar on the surface but are in fact represented similarly.

In our study, participants began by interacting with a computer simulation of a ball that was suspended between two elastic bands, and oscillated horizontally between them (see Figure 3). In addition, there was a fan located to the left of this system that could blow rightward across it, adding an additional force in that direction. Participants were given the goal of using the fan to cause the ball to either (a) stop in the middle between the two poles connected to the ball by the bands or (b) reach the far right-hand side of the system. In either case, the goal could be accomplished by coordinating one’s actions with the inherent frequency of the ball’s oscillations. For instance, by applying the rightward force from the fan only when the ball was traveling leftward, and not when it was traveling rightward, the amplitude of the ball’s oscillations could quickly be reduced and the ball would eventually stop in the middle of the system. (The alternate goal required the opposite strategy, applying force from the fan only when the ball was moving rightward.) Next, participants moved on to a second, seemingly unrelated task

that was quite dissimilar to the ball simulation in a number of important ways. First, rather than being a perceptually rich simulation of moving, interacting parts, the second task was entirely text based. Furthermore, although the ball task displayed actions and interactions unfolding in real time, this task progressed in discrete time steps, controlled by the users’ button presses. Finally, the domain itself was quite dissimilar: The second simulation involved managing the population of a city. Specifically, some participants were assigned the goal of stabilizing the city’s population at 500,000, whereas other participants attempted to reach a population of 1,000,000. To achieve these goals, participants decided whether or not to invest in media advertisements each time step, which would inject a temporary increase in the population level.

verb is missing here, or perhaps "or" should be deleted.

Despite the numerous overt differences between the first and second simulation, they were underpinned by the same underlying dynamics. Both involved oscillatory motion (of the ball or the population) that could be manipulated by a force in one direction, to either stabilize or maximize or the relevant value (ball location or population size). Likewise, the appropriate methods for achieving these goals were completely analogous between the two tasks. We predicted, and found, that participants would achieve the goal in the second task more quickly when it was structurally similar to the goal they were assigned in the previous simulation (e.g., both goals involved either stabilization or maximization). Of interest, participants in our study were unlikely to report noticing the relationship between the tasks, and such noticing was not related to more successful transfer.

We argue that, although the two situations are quite dissimilar from one another on the surface, the physical dynamics of the ball and fan simulation provided a useful mental model for representing the (less overtly spatial) population task. Consistent with this interpretation, when the order of the tasks was reversed (with the more decontextualized population task presented first), no evidence for transfer was observed. In other words, the overtly perceptual and spatial nature of the training task appeared to be critical for this kind of transfer to occur.

Other research is consistent with our general conclusions. For example, Beveridge and Parkins (1987) used a concrete perceptual model to improve performance on a Duncker’s (1945) radiation problem. As noted earlier, previous research

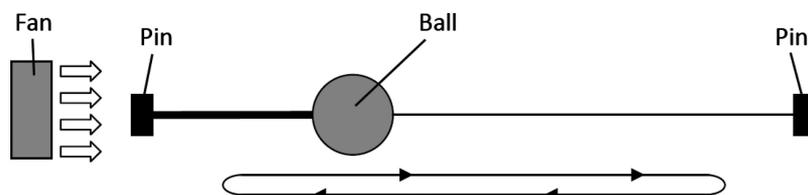


FIGURE 3 Schematic of the ball simulation used by Day and Goldstone. From “Analogical Transfer From a Simulated Physical System,” by S. B. Day and R. L. Goldstone, 2011, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37.

has shown that participants have a very difficult time solving this problem independently and are unlikely to make spontaneous use of relevant analogous examples (Gick & Holyoak, 1980, 1983). However, Beveridge and Parkins found that participants were much more likely to transfer their knowledge successfully when they had previously been shown a physical model that captured the relevant “convergence” structure of the problem. Specifically, they were shown a set of colored transparent strips of plastic that fanned out from a central location, where they overlapped. These strips demonstrated a darker, “stronger” color in that central location, analogous to the greater summed intensity of the converging rays in the radiation problem. Similar results have been obtained after showing an animated diagram depicting moving lines of arrows converging at a central point (Pedone, Hummel, & Holyoak, 2001).

Grant and Spivey (2003), also using Duncker’s radiation problem, demonstrated the important role of online perceptual processing in understanding and transferring knowledge. Those researchers tracked participants’ eye movements while viewing a simple diagram of the described of the situation, with parts labeled *tumor*, *healthy tissue*, *skin*, and *outside*. They found that individuals who successfully solved the problem had spent considerably more time looking at the *skin* area of the diagram, and suggested that this pattern reflected more eye movements crossing the skin boundary while looking between the inside and outside of the body. In other words, successful problem solvers’ eye movements were effectively “acting out” the convergence pattern. Thomas and Lleras (2007, 2009a) subsequently reported achieving similar effects through experimental manipulation. Participants in their studies were more likely to solve the radiation problem after performing a visual task that guided their eye movements (2007) and/or visual attention (2009a) in a convergence pattern on the diagram, alternating between various locations inside and outside the body.

Such perceptual effects on thinking are not limited to visual representations. In fact, a large body of research on “embodied” cognition (see Barsalou, 1999; Glenberg, 1997; Wilson, 2002) has focused on the important relationship between physical action and thought. For example, the “action compatibility effect” (Glenberg & Kaschak, 2002) refers to the fact that individuals’ speed at judging the sensibility of a sentence is influenced by the physical action involved in their response. For instance, participants take longer to confirm that “close the drawer” is a sensible phrase when their response involves a motion toward their own bodies (which is incompatible with the motion required to actually close a drawer). Similarly, Goldin-Meadow and colleagues (see Goldin-Meadow, 2005) have repeatedly demonstrated the importance of gesture in learning and comprehension and have even shown that experimental manipulations of individuals’ gesturing can help or hinder their learning (e.g., Cook, Mitchell, & Goldin-Meadow, 2008). Effects such as these suggest the possibility of similar embodied effects on

problem solving and transfer, and there is some preliminary evidence for this. For instance, just as acting out a passage with physical objects can lead to greater comprehension (Glenberg et al., 2004), Catrambone, Craig, and Nersessian (2006) found that acting out an analog to Duncker’s radiation problem with wooden blocks increased the likelihood of transferring the convergence solution. In a different kind of paradigm, Thomas and Lleras (2009b) found that participants were better able to solve Maier’s two-string problem after performing an exercise which involved swinging their arms, although most participants remained unaware of this effect.

It is important to note, however, that most of the effects described in this section would not necessarily arise from “raw” perceptual representations, containing only information about form, location, color, and so forth. Rather, our explanation assumes that these mental models are integrated representations of both perceptual and meaningful conceptual content. Thinking back to the ball and fan simulation, for example, it is clear that a model based on this simulation would need to include information about properties such as “force” to be effective, properties that are not directly perceivable themselves but must be inferred from the visible components. Furthermore, that particular example requires additional conceptual content in order to assign meaningful directionality to the systems. That is, although the population task that follows it has an inherent positive direction, the ball task is horizontal, with neither direction explicitly “higher” or “lower” than the other. However, as discussed previously, there is evidence that individuals rely on a mental number line that automatically associates the rightward direction with increase. If this conceptual content were included in participants’ mental models of the ball task, it would help to explain the mapping between our two simulations—in both cases, the participants’ interventions would be perceived to provide a net positive force. Consistent with this interpretation, when we ran a follow-up study in which the direction of the fan was reversed, such that it was on the right-hand side blowing leftward across the ball system, no transfer to the population task was observed. A mapping that included this additional conceptual content appeared to be fundamental to the usefulness of the model.

This inherent integration of perceptual and conceptual content also highlights the fact that these mental models are not equivalent to actual perception. A recent study involving physics students (Thaden-Koch, Dufresne, & Mestre, 2006) demonstrated this distinction clearly. In that study, participants observed a simulation of two balls rolling along adjacent tracks. When one of the balls moved in an unrealistic manner—accelerating on an uphill portion of the track—honors physics students were *less* likely to notice this error than were physics novices. In this case, the physics students’ (still-developing) knowledge about the principles operating in the simulation led them to ignore overt perceptual information in favor of their own expectations about the

1795 behavior that “should” occur. We would suggest that these students’ observations may, in fact, be guided by models that are perceptual in that they involve dynamic and spatial representations. However, perceptually grounded models need not be veridical models, and they can possess systematic distortions. With systematic training, the students’ perceptual expectations might be brought into better alignment with the real behavior of the rolling balls, with revisions to their underlying interpretations possibly resulting. Knowledge is both influencing, and is influenced by, perceptual interpretations.

1805 Mathematics provides an interesting domain for examining the interplay between perception and cognition. On one hand, mathematics is, by definition, abstracted from any specific content domain. Ideas such as “three” or “multiplication” are by design theoretically unattached to any particular concrete instantiation. On the other hand, individuals (particularly experts) routinely report a subjectively strong perceptual component to their mathematical reasoning. Because of reports such as these, researchers have recently been giving more attention to the potential importance of perceptual representations and perceptual processing in mathematics. Most of the research conducted thus far has specifically examined the role of perception in the processing of external representations of mathematical concepts, such as equations or graphs.

1820 For instance, Kellman and his colleagues (e.g., Kellman, Massey, & Son, 2009) created an interactive classification task that trained participants to recognize the relevant perceptual features underlying accurate transformations between representations (e.g., matching a graph to an equation). Individuals who completed that task were subsequently much more accurate in generating their own transformations between representations, a crucial step in successful problem solving. Similarly, David Landy and colleagues have focused on the role of perceptual processes in understanding and interacting with mathematical formulas. For instance, in practice, the perceptual grouping of terms (i.e., which terms are closer together in space on the page) can interfere with and even trump groupings based on operator precedence (e.g., grouping by multiplication before grouping by addition; Landy & Goldstone, 2007a, 2007b). On the other hand, experience with mathematical formulas can lead to the automatic deployment of attention to operators with higher priority (Landy, Jones, & Goldstone, 2008). People also appear to *interact* with equations in ways that seem concretely grounded. For instance, students may learn to use a strategy of transposition, or “moving” a term from one side of an equation to the other (and then applying the inverse operation). So, for example, the equation  $5x + 7 = 12$  may be rewritten as  $5x = 12 - 7$  by moving the 7 to the right. There is evidence that for experienced students, this operation is conceived in terms of actual spatial movement. Goldstone et al. (2010) reported a study in which an equation was presented on a computer screen with a subtle moving grating in the back-

ground, and participants were asked to solve the equation for a particular variable. Performance was reliably worse when this grating was moving in the *opposite* direction of the implicated spatial transposition of the term—for instance, when a solution required “moving” a term rightward but the grating was moving to the left. This suggests that the grating’s motion was interfering with participants’ imagined spatial movements of terms within the equation.

Taken together, findings such as these provide a way of extending and enriching our understanding of traditional transfer phenomena while also addressing many of the concerns and critiques that have been raised against the standard cognitivist approach. For example, the suggestion that transfer is often a largely perceptual process is inherently consistent with the idea of “knowing with.” Perception is by nature a process of interpretation, in which existing knowledge structures guide and constrain the organization of new incoming information. Many of the phenomena described in this section could best be explained in terms of providing a model by which new information may be structured and understood (e.g., Beveridge & Parkins, 1987; Day & Gentner, 2007; Day & Goldstone, 2011; Pedone et al., 2001). This differs in important ways from the more traditional account of transfer, which *begins* with the *recognition* of structural commonalities. Instead, perception and action routines can provide the basis for linking two situations, and once linked, more formal, more generalizable structures that are compatible with the linking can be constructed. This kind of mechanism may also underlie the advantage that Kotovsky and Gentner (1996) found for progressively removing perceptual support for connecting two structurally similar situations.

Consistent with construing existing knowledge as a “lens” rather than a focus of cognitive processing, the effects described here frequently appear to be implicit, often occurring without deliberation or even conscious awareness (e.g., Day & Gentner, 2007; Day & Goldstone, 2011; Dreistadt, 1969; Maier, 1931; Schunn & Dunbar, 1996; Thomas & Lleras, 2009b). The notion of perceptually grounded models underlying interpretation also provides a productive way of considering new means for promoting transfer. If transfer between overtly dissimilar situations is possible when those cases involve similar mental models (e.g., Day & Goldstone, 2011), transfer research may be most successful when it focuses on understanding underlying models used by novices and experts in a domain (see Lobato, 2012/*this issue*).

These ideas are consistent with the themes of several of the critiques, and they link particularly well with the ideas and research of Lobato, described earlier (e.g., Lobato & Seibert, 2002). The student described in that example appeared to be forming a model of slope and proportionality as a discrete, integrated unit that could be combined iteratively to fit different situations. Such a model would seem to lend itself to a fairly perceptual, spatial representation. Such a model would also be consistent with her general finding that prior knowledge was not imported wholesale in order to solve an

1905 analogous case, but rather that knowledge provided a means  
of working through and organizing new information—which  
allowed the original model to be simultaneously modified  
and adapted.

1910 A perceptual interpretation of transfer is also consistent  
with the idea that knowledge is not typically transferred from  
a single source. The knowledge that underlies one's under-  
standing of a concrete, analog system seems to exist in a  
variety of independent, sometimes conflicting pieces (e.g.,  
Collins & Gentner, 1987; diSessa, 1982). To the extent that  
1915 comprehension often involves interplay between new facts  
and existing knowledge working together to construct appro-  
priate models (e.g., Clement, 1988), transfer may often draw  
on a lifetime of knowledge and experience. This fits well with  
the analysis by Carreher and Schliemann (2002) described  
previously. Students in their research were informed and in-  
1920 fluenced by knowledge from multiple domains at once, and  
their learning involved an active process of novel integration  
across those domains. Of course, this is not to say that such  
"interpretation"-based transfer invariably relies on multiple  
sources. As with literal perception, interpretation may also  
1925 sometimes rely heavily on a single recent episode (e.g., Day  
& Gentner, 2007; Day & Goldstone, 2011, Schunn & Dunbar,  
1996).

Our goal in this section has not been to suggest that percep-  
tual representations are "the" basis for knowledge transfer,  
1930 or that they supply an explanation for the many varied find-  
ings and phenomena reported in the transfer literature. Al-  
though such a conclusion would necessarily follow from the  
strongest claims that all of cognition is inherently perceptual  
(e.g., Barsalou, 1999), there is at present simply not enough  
1935 empirical data to support make this argument convincingly.  
Nor are we suggesting that the path to improved transfer is  
to make learning materials more "perceptual." In fact, there  
is considerable evidence discussed earlier in this paper that  
explicitly contradicts this conclusion. Rather, we would ar-  
1940 gue that acknowledging and leveraging learners' perceptual  
representations, particularly as they relate to mental models  
of learned material, is one important, effective, and largely  
unexplored means of supporting transfer.

## CONCLUSIONS

1945 In this article, we have tried to organize the diverse litera-  
ture on knowledge transfer into a coherent whole. Obviously,  
however, these broad-ranging ideas and findings sometimes  
defy straightforward integration. For example, as researchers  
and educators continue to struggle with the challenges of  
1950 helping students to achieve generalizable knowledge, it is  
clear that the critiques of the more traditional models of  
transfer will need to be taken seriously. It is also possible that  
by recognizing different approaches as being reflective of dif-  
fering goals or levels of analysis, and honestly considering  
1955 both the advantages and weaknesses of different perspec-

tives, it will prove to be the case that no single approach is  
sufficient to account for all aspects of transfer. However, as  
transfer researchers of all stripes continue to become more  
open and creative in their search for explanations and so-  
lutions, the development of theories and principles that are 1960  
both very general and highly effective remains an enticing  
possibility. As the other articles in this special issue make  
clear, the coming decade promises to be a productive and  
exciting period for transfer research.

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delete "make" or add "or" after "support"

add "by" before "honestly"

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# Seeing Deep Structure From the Interactions of Surface Features

Michelene T. H. Chi and Kurt A. VanLehn

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- Q8.** Au: Reed (2012): Provide journal volume number.
- Q9.** Au: Schartz et al.: Please update this (in press) reference if its status has changed.
- Q10.** Au: VanLehn & Chi: Please update this (in press) reference with year and chapter page range if its status has changed.

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*Michelene T. H. Chi and Kurt A. VanLehn*

# Seeing Deep Structure From the Interactions of Surface Features

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Transfer is typically thought of as requiring individuals to “see” what is the same in the deep structure between a new target problem and a previously encountered source problem, even though the surface features may be dissimilar. We propose that experts can “see” the deep structure by considering the first-order interactions of the explicit surface features and the second-order relationships between the first-order cues. Based on this speculative hypothesis, we propose a domain-specific bottom-up instructional approach that teaches students explicitly to focus on deriving the first-order interactions cues and noticing the second-order relationships among the first-order interaction cues. To do so, researchers and instructional designers need to first extract from experienced solvers or experts how they derive such first-order cues. Transfer is assumed to be based on the similarities in the second-order relationships, which are familiar everyday relationships such as equal to, greater than, and so forth.

Transfer can be broadly construed as the ability of individuals to “treat” a new concept, problem, or phenomenon as similar to one(s) they have experienced before. The term “treat” can be used broadly to refer to performing various tasks such as categorizing, deciding, diagnosing, explaining, identifying, learning, problem solving, and analogical reasoning in or across different contexts, concepts, problems, patients, phenomena, or situations. For example, if students have learned to explain one phenomenon correctly, can they then explain another similar phenomenon, thereby exhibiting transfer? Transfer can also be construed more specifically as consisting of two sets of processes: *initial learning* followed by *reusing or applying what was learned*. In this article, we propose a new hypothesis for why transfer often fails in the classic “two-problem transfer paradigm,” and we suggest an instructional approach that may remediate the “failure-to-transfer phenomenon.” We begin by briefly describing these terms next.

## THE FAILURE-TO-TRANSFER PHENOMENON IN THE TWO-PROBLEM TRANSFER PARADIGM

The majority of research on transfer focuses on the procedural task of problem solving, such as, if students have

learned to solve one algebra problem, are they able to transfer that knowledge by solving another algebra problem that has the same underlying deep structure? In this section, we briefly describe the *failure-to-transfer phenomenon* in this classic context which has sometimes been referred to as the *two-problem transfer paradigm* (Lave, 1988).

In the typical two-problem transfer paradigm, students are first asked to attempt to learn and solve a source problem A (such as learning by reading a solution or worked-out example to Problem A, or learning by solving Problem A successfully), and then students are asked to solve a novel target problem X that has the same deep structure as problem A. By and large, the surface features of Problem A and the target problem X are different, and the transfer of knowledge from the source problem to the target problem is often difficult. For example, in the context of algebra word problems, students may learn to solve Problem A by describing the surface features of Problem A (such as the two cars moving in the same direction, at different speeds, with the goal of the second car to overtake the first car). To solve Problem X only if the surface features of Problem X are the same as the surface features of Problem A (or are literally similar), students may solve Problem X only if they notice the same procedure). That is, the transfer of knowledge from the source problem to the target problem is often difficult because the surface features of the source problem and the target problem are different. For example, in the context of algebra word problems, students may learn to solve Problem A by describing the surface features of Problem A (such as the two cars moving in the same direction, at different speeds, with the goal of the second car to overtake the first car). To solve Problem X only if the surface features of Problem X are the same as the surface features of Problem A (or are literally similar), students may solve Problem X only if they notice the same procedure). That is, the transfer of knowledge from the source problem to the target problem is often difficult because the surface features of the source problem and the target problem are different. For example, in the context of algebra word problems, students may learn to solve Problem A by describing the surface features of Problem A (such as the two cars moving in the same direction, at different speeds, with the goal of the second car to overtake the first car). To solve Problem X only if the surface features of Problem X are the same as the surface features of Problem A (or are literally similar), students may solve Problem X only if they notice the same procedure). That is, the transfer of knowledge from the source problem to the target problem is often difficult because the surface features of the source problem and the target problem are different. (We elaborate more next the operational definitions of surface features and deep structures, as used in the literature.)

“more next”  
seems very hard  
to parse, and  
more is  
redundant with  
elaborate;  
therefore, remove  
“more”

delete  
comma

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However, the majority of studies using variations of the classic two-problem transfer paradigm show that transfer fails when the two problems are dissimilar at the surface level but similar at the deep structural level. The typical finding seems to be that after students have succeeded in solving a source problem, they cannot then solve a target problem successfully that is slightly different at the surface level (Catrambone & Holyoak, 1989; Gick & Holyoak, 1980, 1983; Reed et al., 1985; Ross & Kennedy, 1990) even though they have the same underlying deep structure.

The point is that regardless of whether one takes a cognitive or an alternative perspective on transfer (see Reed, 2012), this *failure-to-transfer phenomenon* needs to be explained rather than dismissed as a contrived lab-based paradigm, especially because many standard texts used in school curricula adopt this mode of assessing transfer. For example, students are often asked to learn how to solve problems by studying worked-out solution examples either presented in their texts or worked-out by their teachers at the whiteboard, and then they are either tested for their understanding or asked to practice as homework by solving additional problems (provided either at the end of the chapter or by the teachers) that are either similar or dissimilar in the surface features. Therefore, this traditionally used laboratory-based two-problem transfer paradigm is a somewhat authentic paradigm. In short, the failure-to-transfer phenomenon is ubiquitous in school settings and needs to be explained.

The failure-to-transfer phenomenon is surprising because the assumption is that students should have been able to “see” (as experts can) that the target problem *X* and the source problem *A* are similar at a deep level, thus allowing them to retrieve the procedure learned from and used in source problem *A*, then apply this retrieved (or could be modified) procedure to the target problem *X*. In contrast to the failure-to-transfer phenomenon in problem-solving research, in categorization research, it has been shown that participants can categorize a new instance successfully even when there is no visual similarity with a prior instance, but there is some underlying theory-based similarity. For example, if we know how intoxicated people tend to act, then we might categorize a fully clothed man jumping into a swimming pool as a drunk (Murphy & Medin, 1985), especially if the context is a pool party with lots of available alcohol, even though this particular intoxicated person’s behavior does not resemble that of other drunks one has seen. Thus, participants are usually able to “transfer” by categorizing “a clothed man jumping into the pool” as the same as “a man talking loudly and wildly in a bar,” even though they look and act very differently and are seen in different contexts.

Thus, broadly conceived, the processes of transfer require that students abstract or understand the deep structure of the first problem and then recognize that the second problem also has the same deep structure, therefore the procedure associated with such a deep structure then applies. Thus, for the

purpose of understanding our hypothesis on instruction and learning, we simplify transfer in problem solving as constituting these two broad sets of processes (as stated earlier): The first set of processes can be called *initial learning*, and the second set can be referred to as the processes of *reusing* or *applying* what had been learned. Before we can entertain hypotheses for the failure-to-transfer phenomenon, we need to describe the difference between surface features and deep structures, as used in the literature.

### Surface Features Versus Deep Structures

Researchers pretty much agree that “surface features” refer to literal objects, concepts, or entities explicitly described in a problem statement or a situation, sometimes also referred to as the cover story. However, many different ways of defining “deep structure” are offered in the context of different studies and different domains. In the problem-solving literature, deep structure often refers to the procedure for solving a problem. For example, in probability problems, whether a problem involves a combination principle or a permutation principle has been considered the deep structure, whereas the cover stories that described the problems in the context of marbles and cars are usually considered the surface features (Ross, 1987). Thus, traditionally, for problem-solving research, if two problems or solution steps are generated by the same rule, then they share the same deep structure (Muldner & Conati, 2010). In such a definition, a rule can be an equation such as  $\text{rate}_1 \times \text{time}_1 = \text{rate}_2 \times \text{time}_2$  (Reed et al., 1985) for a math distance problem, or a principle such as Newton’s Second Law for physics problems (Chi, Feltovich, & Glaser, 1981).

Besides rules, there are many other ways to define deep structure. One other way to define a deep structure is in terms of a schema. In the classic Gick and Holyoak (1980, 1983) studies, when a problem solver successfully solved the fortress problem (in which a general needs to capture a fortress by dividing the army and converging on the fortress from many sides), the hope was that the solvers had induced a “convergence” schema that could be reused to solve a new tumor problem (in which rays can be divided into weaker strengths so they will not kill healthy tissue, yet they can converge and destroy the tumor). Another alternative way to define deep structure in problem solving is to consider not just rules that generate a solution (such as a formula to compute density) but rules that are more conceptual and abstract, such as learning rules that *density is invariant under transformation* (Schwartz, Chase, Opezzo, & Chin, 2011).

In non-problem-solving research, deep structure also has been defined in other ways. For example, in understanding stories, the surface features would refer to the setting and objects, whereas the deeper structure would refer to the structure of the causal plot (Gentner, Rattermann, & Forbus, 1993). In learning studies, deep structure has been defined as the men-

tal models that students have constructed. For example, in learning about the human circulatory system (Chi, de Leeuw, Chiu, & LaVancher, 1994), students' deep understanding can be assessed as the correctness of the mental model that can be depicted to represent their understanding of the circulatory system. Similarly, in work on students' learning of science processes, two schemas were described as relevant to students' understanding: an "emergent" schema and a "direct" schema. These schemas would constitute the deep structures for various science processes (Chi, Roscoe, Slotta, Roy, & Chase, 2012).

In categorization research, deep structure has also been defined in terms of the first-order relationships between two objects, things, locations, arguments, or more generally, two entities (Gentner & Kurtz, 2006; Gentner & Markman, 2006). Thus, two objects have the same deep structure if they invoke the same relationship even though they can be superficially dissimilar. For example, a bridge or bridging is a relationship that connects two things, and the things can be two locations, two concepts, or two entities. This means that a wooden plank has the same relational structure (because it connects two locations) as a dental bridge (that connects two teeth). Thus, a dental bridge and a wooden plank share this relational similarity whereas they share little, if any, intrinsic similarity, or similarities of features of the entities. An intrinsic feature of the wooden plank bridge might be that it is made of wood or it is wide enough for people to walk on, whereas an intrinsic feature of a dental bridge is that it permanently joins adjacent teeth or dental implants.

In sum, there are many ways to identify and define the deep structure of concepts, categories, entities, problems, phenomena, and situations. Its main difference from surface features is that the surface features can usually be perceived whereas the deep structures often cannot be directly perceived.

### Lacking Deep Initial Learning of the Source Problem

One obvious explanation for the discrepancy in the failure of transfer in the context of the two-problem transfer paradigm compared to the success of transfer in other tasks such as categorization is that initial learning was not deep. Let's call this the *lacking-deep-initial-learning* hypothesis. There is agreement among multiple perspectives (such as a cognitive, a situative, or an embodied perspective) and multiple researchers on this explanation. For example, from a cognitive perspective, Ross (1987) stated,

Assume that novices are trying to make an analogy between the current and past problem, but that they *do not have a good understanding of the appropriate problem structure* [emphasis added], . . . in this case, novices may rely on superficial similarities of the problems to decide how to set up the correspondences between problems. (p. 630)

From a situated perspective, Engle (2006) said, "First consider the crucial issue of whether students' *initial learning* [emphasis added] of the relevant content was successful enough to provide a substantive basis for them to have transferred what they learned to next context" (p. 453). Similarly, Lobato (2006) suggested that "transfer from the actor-oriented perspective is the influence of learners' prior [*initial learning*] activities on their [*subsequent*] activity in novel situations" (p. 437). But more explicitly, Lobato's opening sentence stated that "a central and enduring goal of education is to provide learning experiences that are useful beyond the specific conditions of *initial learning*" (p. 431). Likewise, Marton (2006) stated that "transfer is about how what is learned in one situation [*initial learning*] affects or influences what the learner is capable of doing in another [*subsequent*] situation" (p. 499). In short, regardless of perspectives, it is commonly assumed that transfer first requires deep initial learning of the source problem A before one can expect successful transfer to the target problem X.

This lacking-deep-initial-learning hypothesis should predict that if students did learn the source problem deeply, then they would be able to transfer more successfully than if they did not learn it deeply. One way to substantiate this hypothesis is to consider how participants were asked to learn the source problem. In many classic studies using the two-problem transfer paradigm, it becomes apparent that students were not required to learn the initial problem deeply. For example, students were often asked to either *read* a provided solution to the source problem (Gick & Holyoak, 1980) or *attempt* to solve and then *read* a provided solution (Reed et al., 1985). Reading a solution clearly does not imply that students have understood the example. In a framework that Chi (2009) introduced that differentiates various overt modes of engagement with learning materials as either *passive* (*receiving* information only), *active* (*selecting* information for emphasis), *constructive* (*generating* new information), or *interactive* (*collaboratively constructing* or *co-constructing* new information), reading is considered a *passive* overt engagement activity in which students only receive information, whereas generating a solution or self-explaining each solution step is considered a *constructive* engagement activity, which engenders greater learning. This ICAP framework (with the ICAP hypothesis that *interactive-I* mode of learning is better than *constructive-C*, which is better than *active-A*, which in turn is better than *passive-P*) thus suggests that reading a solution example alone is not a good enough learning activity to engender deep learning (Chi, Bassok, Lewis, Reimann, & Glaser, 1989).

The ICAP hypothesis can also interpret the results of Gick and Holyoak's (1983) third experiment. The results of the third experiment show that students manifested greater transfer if they *provided their own solution* to the source problem rather than merely *reading* the solution to the source problem, because reading a solution is a *receiving* mode of learning,

whereas providing a solution is a *generative mode*. Therefore, providing their own solutions led to deeper initial learning, and deeper initial learning did foster greater transfer, thus providing direct evidence in support of the lacking-initial-deep-learning hypothesis.

The preceding paragraph suggests that deep learning cannot be guaranteed by having students *read* the solution steps. Deep learning also cannot be accurately assessed merely by seeing if students can solve the first problem successfully, because the correct solution can arise from copying an example solution, or from retrieving a similar solution. Both would be classified as the *active* mode of learning, in which students *copied* a solution or *retrieved* the steps of a prestored solution (neither of which is *generative*). There is considerable evidence showing that being able to solve a problem without error (i.e., knowing the procedure) does not necessarily imply that one has understood the deep structure of a problem. For example, Kim and Pak (2002) found no correlation between problem-solving ability and understanding of concepts such as force and acceleration after students have solved on average 1,000 mechanics problems. Similarly, Nurrenbern and Pickering (1987) found a lack of relationship between solving numerical chemistry problems and understanding the molecular concepts underlying the problems. Thus, the results of many studies suggest that successfully solving an initial problem (in a transfer paradigm) so that students have acquired the procedure for solving an initial source problem does not guarantee that students have actually learned the underlying deep structure of the initial problem, such as the principle or concepts underlying the procedure.

Consistent with the deep-initial-learning hypothesis, studies that have directly assessed students' initial understanding of the source problems also have shown conclusively that the representation (or understanding) that students had of the initial problem determined the degree of transfer. This was shown clearly in Gick and Holyoak's (1983) fourth experiment. In that experiment, they provided two source stories and asked participants to write down ways in which the two stories were similar, and then the quality of their descriptions were rated in terms of good, intermediate, or poor. Good means that the basic idea of convergence was present. The results were very pronounced and clear: 91% of the participants who wrote a good description could solve the target problem even without a hint, as compared to 30% of the participants who wrote a poor description. This result seems unequivocal in showing that if participants understand source problems deeply, then they are more able to transfer. Similar results were also obtained by Novick and Holyoak (1991). Thus again, there seems to be direct evidence in support of the lacking-initial-deep-understanding hypothesis.

As just pointed out, because there is general agreement among researchers that failure-to-transfer reflects a lack of deep initial learning, and there is evidence to show directly that deeper initial learning leads to greater transfer, then the problem of failure-to-transfer becomes a problem of how to

foster deeper initial learning. The next section focuses on methods that have been used to foster deeper initial learning.

### Instructional Methods That Fostered Deeper Initial Learning Successfully

Many well-known concrete instructional methods that succeeded in fostering transfer did so basically by enhancing initial learning. One method is to provide two source examples, and furthermore to ask students to explicitly compare and contrast the two source examples so that they are more likely to be able to abstract the underlying structure (Gick & Holyoak, 1983; Schwartz et al., 2011). Another method is to ask students to self-explain a worked-out solution example of the source problem (Chi et al., 1989). A third method is to require students to identify, for every written step in a solution, the deep principle that generated it (Min Chi & VanLehn, 2010; VanLehn & Chi, in press). In all these cases, transfer successes improved.

The successes of these methods at enhancing transfer can be explained generally by the ICAP framework, in that the students were asked to be more *constructive* in the initial learning processes. Recall that *constructive* activities refer to activities undertaken by students that generate knowledge beyond the information given, such as drawing a diagram when none was provided by a problem, self-explaining a worked-out solution, identifying the deep principle that justifies every step, or comparing and contrasting two problems, as such comparisons and contrasts produce similarities and differences that were not explicitly stated in the two source problems (Chi, 2009). Constructive activities typically foster deeper understanding and learning, which then lead to greater transfer.

Despite the successes of these general instructional methods that encourage *constructive/generative* activities, these instructional approaches do not explain how deep initial learning is achieved. More specifically, these constructive/generative methods do not address one crucial dilemma, which is that experts or experienced problem solvers can "see" the deep structure of a problem but novice solvers cannot. Being able to see the deep structure obviously enhances transfer. Might there be a more specific instructional method that can enhance students' deep initial learning to the point that they can "see" a problem's deep structure and thereby transfer? We address this dilemma next.

### HOW CAN EXPERTS "SEE" THE DEEP STRUCTURE?

The dilemma is, when given the exact same problem statement, experts can "see" the deep structure, whereas novice learners cannot (Chi et al., 1981). We assume that the ability to "see" the deep structure of a problem is an outcome of having learned the materials with deep understanding. The

change "h" in "How" to lowercase.

385 question is, How can experts "see" the deep structure and  
how can instruction facilitate novice students to "see" the  
390 deep structure as well? In this section, we explore an alternative hypothesis and suggest how it might translate to instruction. We start by describing novice students' success at "seeing" the relevant surface features, in contrast to their inability to "see" the deep structures.

### Students Can See the Relevant Surface Features

delete comma

395 Although everyone agrees what surface features refer to in a problem statement, there is very little discussion about whether students can pick out the *relevant* from the less relevant or *superficial* surface features, because obviously not all surface features are relevant or important for the problem solution. Suppose a math problem is about how fast a pickup truck is traveling (Ross, 1987); in such a problem, the surface features are the truck, the speed at which the truck is traveling, the time it started, and so forth. Obviously the pickup truck is a superficial surface feature whereas the speed and time are relevant surface features.

405 We have some evidence to suggest that students are capable of differentiating relevant from irrelevant (or superficial) surface features. The evidence shows that novice students (assuming they have shallower understanding) are just as competent as experts (assuming they have deeper understanding) at distinguishing relevant from superficial surface features.  
410 We base this conjecture on the following finding. In Study 8 of Chi, Glaser, and Rees (1982), six expert students (graduate students) and six novice students (who had completed one course in mechanics with at minimum a B grade) were asked to first judge (rate on a 1–5 scale) how difficult each of the 20 physics problems presented to them were (these problems did have different underlying physics principles), and then identify key words or phrases that helped them reach their decisions on a problem's difficulty.

420 The surprising finding was that there were no major differences, in that both the experts and the novices were equally facile at picking out the important or relevant surface features in the statements of the physics problems, such as "horizontal force," "frictionless," and "move together." For 19 of the 20 problems, the expert and novice students circled the same set of words or phrases in the problem statement. Only in seven of the 20 problems did the experts identify 1.6 additional features, whereas in 13 of the 20 problems, the novices identified an additional 2.1 features as important. In other words,  
430 it was not the case that experts picked out one set of surface features as important or relevant, whereas novices picked out a different set of literal features.

435 This finding presents an important dilemma. That is, if the experts' superiority is in "seeing" the deep structure of problems, but novices were equally facile at identifying relevant

change "seven" to "7" to keep consistency with the number/category rule (all numbers under 10 have to be written out, not unless the number < 10 is in relation to a number > 10 of the same category. In this case, 20 and 7 are both being used to refer to the same category, which is "problems," so you have to change the "seven" to a "7.")

beyond the surface features? We propose a novel hypothesis to address this dilemma.

### Deep Structure Is Derived From Perceiving Interactions of Surface Features: A Novel Hypothesis 440

The hypothesis we propose here is that experts can "see" the deeper cues by considering the *interactions* of the explicit surface features. Again, we use the term "features" here to refer to words, concepts, or phrases that are explicitly stated as relevant (as just described), and the term "cues" to refer to deeper structural concepts, rules, or principles that must be derived, inferred, or computed. This hypothesis is based on insights that can be gleaned from analyzing what domain experts see when they solve problems. The insights are suggested by both the results of Study 7 in Chi et al. (1982; also reported as Study 4 in Chi et al., 1981) and Study 8 (Chi et al., 1982).

455 In Study 7, two novice students (who had completed a basic college mechanics course with an A grade) and two expert physicists (who had frequently taught introductory mechanics) were asked to state the "basic approach" they would take to solve the same 20 problems (without defining for them what "basic approach" meant). Moreover, they were also asked to state the problem features that led them to their choice of basic approach. In contrast to the task described previously of asking students to circle the relevant key features in the problem statements (Study 8, Chi et al., 1982), for which there were no differences between novices and experts, in this task there were overwhelming differences between the experts and novices in the key features they verbally cite contributing to their decisions about the basic approach to the solution of the problems. In fact, none of the key features cited by the novices and experts overlapped. Not surprisingly, novices, again, mentioned the literal surface features such as objects and concepts that were explicitly stated in the problems, such as "pulleys," "friction," and "gravity." Experts, on the other hand, stated deeper structural cues such as "it's a before-and-after situation." These have been called *derived cues* (see Table 11 in Chi et al., 1981).

475 There are a few different ways to characterize the differences in the derived cues and surface features that the experts and novices "see." One general way is to say that the experts identified and "saw" more *process* cues than novices (74 process cues for experts vs. two for the novices), and novices saw more *entity* cues than experts (39 entity cues for novices vs. 21 for experts; Chi, 2011). Examples of *process* cues cited by both experts were a "before-and-after situation" and "inelastic collision," and examples of *entity* cues cited by both novices were "friction" and "spring." *Processes* and *entities* are distinct ontological categories that are difficult for students to shift across, thereby reinforcing the difficulty of helping students "see" a process cue (Chi, submitted).

change "two" to "2" - number/category rule

This whole sentence has ambiguous subjects, unclear transitions, and improper verb agreement. See changes in CAPS - "... Rule III) EVEN THOUGH THEY DID NOT KNOW how WEIGHT AND DISTANCE DIMENSIONS INTERACTED until THEY GOT OLDER, WHICH WAS when they can... etc"

verb agreement - change "muddled" to "muddle"

490 However, characterizing the cues that experts see (e.g., "a  
before-and-after situation") as a *process* cue does not tell us  
how experts see them. We propose that an additional way to  
characterize process cues is that they represent *interactions*  
among the surface features or the literal objects and entities.  
495 We now describe five findings that can be reinterpreted as  
showing the skill of seeing the interactions among features.  
insert comma  
500 st, when physics experts mention a cue such as a "before-  
and-after situation" in the study just described, not only is  
this cue not explicitly stated in the problem description, but  
such a cue must be derived from surface features contained in  
a problem description such as "The cart starts from rest and  
rolls down the ramp" and "When the cart reaches the bottom  
of the ramp, it is moving at 2 m/s." Somehow, the surface fea-  
505 tures embodied in the mentally conceived situation (or mental  
model) can generate the energy information needed for two  
conditions, when the cart was at rest (the initial condition)  
and when the cart reached the bottom of the ramp (the final  
condition). Thus, experts can derive the energy information  
at the initial and final conditions (what is referred to as first-  
510 order cues). Once derived, these first-order cues allow the  
expert to "see" or know that the mechanical energy (kinetic  
+ potential) at one time point is *the same* as the mechan-  
ical energy at the other time point. (Later, this equivalence  
relationship will be referred to as a second-order cue.) The  
515 equivalence of the two energy quantities must have led to the  
cue of a "before-and-after situation," meaning that the energy  
*before* the cart rolls down is the same as the energy *after* the  
roll. The point is that it is the interaction between two surface  
features that yield the first-order and second-order cues. We  
520 unpack this example further next.

A second example comes from the domain of chess. When  
novice chess players see a chess board in the middle of a  
game, they do see the relevant pieces (such as the Queens  
and the Kings), where they are located on the board, and  
525 maybe which other pieces are adjacent and nearby. However,  
when an expert sees a chess board in a middle game position,  
they also see the complicated interactions among the pieces.  
Chase and Simon (1973, p. 234), for example, showed that  
an expert player can see "abstract" attack interactions that  
530 involve a combination of pieces of the same color converging  
on the opponent's King position. Novice players presumably  
do not see these "abstract" attacks that depict complicated  
interactions.  
make "middle" and "game" one word

This third example is a developmental study that illus-  
535 trates more directly that seeing the interactions of dimen-  
sions leads to more successful problem solving. In Siegler's  
(1978) study, he asked children of different ages to predict  
which side of a balance scale would go down when varying  
weights are placed on pegs at varying distances on two sides  
540 of the fulcrum. Younger children tended to make predictions  
based on either the weight or the distance dimension (i.e.,  
using Rules I and II). However, older children were able to  
consider both the weight and the distance dimensions (us-  
ing what he called Rule III), although not knowing precisely

how they interact until even older when they can use Rule 545  
IV. Rule IV usage showed that children could compute the  
torques on each side by multiplying the amount of weight  
on each peg by the peg's ordinal distance from the fulcrum.  
In short, this study showed clearly that success at solving  
550 this balance scale problem depended on children's ability to  
consider the interaction of two dimensions. In using Rule  
III, even though they could consider only the interactions  
of weight and distance in a vague subjective way, causing  
them to simply "muddled through" when the two dimensions  
555 conflicted (Siegler, 1978, p. 114), children using Rule III  
were nevertheless more advanced than children using Rule  
I or II, in that they were more prepared to advance to Rule  
IV. The point here is that simply considering the interaction  
between two dimensions, even without knowing exactly how  
560 they relate, made these children more advanced than younger  
children who only considered one dimension at a time.

For a fourth example, we apply the same interpretation to  
a transfer study described by Schwartz, Chase, and Brans-  
565 ford (in press). In their clown study, middle-school students  
in both conditions were given the same pairs of problems to  
either practice applying a formula to find the density of a  
pair of buses that exhibited the same ratio (the apply condi-  
tion) or invent a crowdedness (density) index by comparing  
and contrasting these same pairs of buses (the invent condi-  
570 tion). Students in the invent condition exhibited far greater  
transfer in terms of their understanding of the ratio structure  
that comprises density. To invent the density index, students  
in the invent condition must have considered the relation-  
ship between the number of clowns and the number of bus  
575 compartments (or volume).

Finally, the failure of novice students to consider interac-  
tions can be explicitly shown by the finding in Study 5 of Chi  
et al. (1982). In that study, four physics experts (two college  
professors, one postdoc, and one 5th-year graduate student)  
580 and four novice students (who had completed the introduc-  
tory physics course with a B grade, using the Halliday &  
Resnick, 1974, text) were simply asked to summarize Chap-  
ter 5 on particle dynamics of Halliday and Resnick (1974).  
Because this chapter introduced Newton's three laws, all par-  
585 ticipants mentioned the three laws so that we can compare  
what they say about each law. The textbook was available to  
them while they summarized out loud for 15 min. There were  
no differences between the experts and novices in terms of  
quantitative measures such as the length of their summaries  
590 or the number of quantitative relations mentioned. However,  
a content analysis revealed important differences. We illus-  
trate with an example of their summary of Newton's Third  
Law.

In the 1974 version of the text, Newton's Third Law was  
595 stated as "To every action there is always opposed an equal  
reaction: or the mutual actions of two bodies upon each other  
are always equal, and directed to contrary parts." We de-  
composed this Law into five major components with the  
important concepts italicized as follows: (a) the reaction is

insert comma

600 *opposite in direction*, (b) the reaction is *equal in magnitude*,  
 (c) action-reaction involves the mutual actions of *two gen-*  
*eral bodies*, (d) action-reaction are general forces *extended*  
*by each body on the other*, and (e) the direction of action-  
 605 reaction is *a straight line*. Because seven out of the eight  
 participants did not mention component (e), we ignore this  
 fifth component. Among the first four components, we might  
 agree that components (c) and (d) are relevant to interac-  
 tions, whereas components (a) and (b) are not relevant to  
 interactions (because they refer to notions of *opposite* and  
 610 *magnitude*). The results show that both the expert and novice  
 students (all eight of them) mentioned component (a), and all  
 four experts and three of the novices (totaling seven) men-  
 tioned component (b). However, none of the novice students  
 mentioned either components (c) or (d), whereas three of  
 615 the four experts mentioned both components (c) and (d). In  
 short, the findings show clearly that to understand this Third  
 Law deeply, one must understand the interaction aspects of  
 the Third Law, as the experts were able to articulate.

Collectively, the findings of these five studies all suggest  
 620 that to understand some principles or solve some problems  
 successfully, students must consider the interactions among  
 some literal features. Thus, the hypothesis we propose here  
 is that experts can “see” the underlying principle or deep  
 structure of a problem because they can derive the higher  
 625 order cues based on the *interactions* of the surface features,  
 in which the surface features can be directly perceived (e.g.,  
 the weights and distance in the case of the balance scale).

This hypothesis differs from alternative hypotheses that  
 have been proposed. For example, for Siegler’s developmen-  
 630 tal findings, the superior ability of older children to use Rule  
 III and IV had sometimes been attributed to children’s men-  
 tal capacity that develops with age (Case, 1974). In our own  
 earlier work (Study 8; Chi et al., 1982), the fact that experts  
 can “see” the deep structures of problems were hypothesized  
 635 to arise from experts having acquired causal inference rules  
 that related explicit problem features directly with derived  
 cues and principle, in a linearly causal way, without consid-  
 ering the interactions of the literal features. For example, we  
 had assumed that literal cues such as “frictionless” would  
 640 lead directly to the derived cue of “not having dissipative  
 forces” and then subsequently to the principle of Conserva-  
 tion of Momentum/Energy, without assuming that “friction-  
 less” may interact with other literal features in the problem.  
 The next section proposes an instructional approach based  
 645 on our hypothesis.

### AN INSTRUCTIONAL THE HYPOTHESIS INTERACTIONS

650 Our hypothesis of the importance of focusing on interac-  
 tions of literal features may suggest alternative methods of  
 instruction. In contrast to the general constructive/generative

instructional methods described earlier, such as comparing  
 and contrasting or self-explaining, which are effective over-  
 all for all types of tasks and domains, the general construc-  
 tive/generative instructional approaches can be enhanced in 655  
 a way that is tailored specifically to our hypothesis. A di-  
 rect instructional implication of our hypothesis is to teach  
 students explicitly to focus on the interactions among the rel-  
 evant literal surface features as a way to “see” and understand  
 the deep structure. This requires that students learn to *derive* 660  
 first-order cues.

### Deriving First-Order Interaction Cues

Our instructional proposal can be illustrated in the case of  
 the clown study again (Schwartz et al., in press). In that task, Q5  
 eighth-grade students were told to either apply a formula to 665  
 find the density of each bus company or to  
 invent a density index for the buses. For  
 they were given the formula that densi-  
 of objects divided by the volume (whi-  
 670 tity). For the invent condition, students were asked to come  
 up with a procedure to find out how crowded the buses for  
 a company are. An instructional approach that is intermedi-  
 ate between these two approaches (apply vs. invent) is the  
 one proposed here: In addition to being asked to invent a 675  
 crowdedness index, students receive the hint to look for in-  
 teractions among relevant dimensions. That is, they would  
 be asked to think about how the relevant dimensions relate  
 to each other. Based on our earlier results showing that  
 novice physics problem solvers could in fact pick out the  
 relevant surface features, we surmise that students will not 680  
 have difficulty picking out the relevant dimensions (in this  
 case, number of clowns and number of bus compartments),  
 but what they must look for in addition is the way those  
 dimensions interact. (Using Siegler’s balance scale task as  
 an example, this hint is analogous to scaffolding students to 685  
 consider interactions of two dimensions, the clowns and the  
 bus compartments; that is, to push them to consider Rule  
 III.) Although this instructional method should be even more  
 effective than the invent instructions without the hint to look  
 for interactions, the point of the example is merely to illus- 690  
 trate how instruction can draw students’ attention to focus  
 on interacting surface features, thus expediting acquisition  
 of first-order cues.

For another example, consider again the cart-ramp physics  
 695 problem:

A cart starts from rest and rolls down the ramp. When the  
 cart reaches the bottom of the ramp, it is moving at 2 m/s.  
 Neglecting all sources of friction (air, rolling, etc.), what is  
 the height of the ramp? (Assume that the mass of the cart is  
 5 kg.) 700

The surface features are the cart, the ramp, air friction, and  
 so forth, and we assume that novice students are capable of

Should this be  
 "were"?

change "were" to "was" for  
 subject-verb agreement.

705 imagining the dynamic situation of a cart gaining speed as it rolls down a ramp. This dynamic image can be conceived of as the student's mental simulation of the situation described in the problem. (Note that because this dynamic situation is relatively simple, students can form an accurate mental model of it readily, in contrast to our earlier study, in which students had to learn to form a complicated correct model of the human circulatory system; Chi et al., 1994.)

710 We postulate that students will not have as much difficulty learning to ascertain from their mental simulations that there are two time points: The initial time when the cart is at rest at the top and is at the bottom of the ramp. The surface features that are relevant at each time point are the cart's mass, velocity, and height. Because the height at the final time is zero (because cart is at the bottom of the ramp), the energy at the final time is a function of the cart's mass and its velocity (both are given quantities), which are related by the equation  $E = m \cdot h \cdot g + 0.5 \cdot m \cdot v^2$ . In essence, this equation allows students to derive the first-order interaction cue of the final energy. But even before considering the interactions of the relevant features, students are often required to infer some of their values. For

715 example, students need to infer that the height at the final time because *the cart reaches the bottom of the ramp* and to infer that the initial velocity of the cart is also zero because *the cart starts from rest*. For the initial time, even though the value of height is unknown, students can still be

720 taught to derive it by considering the interactions among the cart's velocity, mass, and height, as specified in the same equation. As indicated earlier, these energies are referred to as the first-order interaction cues, and students can be taught to derive them from the surface features.

725 The hypothesis is that novice students should be taught explicitly to focus on deriving first-order cues based on the interactions of the surface features described in the problem statement. Such an approach may have other benefits, such as helping students to overlook similarities in the surface features, when the deep structures differ. This is a situation in which two problems look almost identical but in fact have very different deep structures. In such a case, students need to be able to overlook surface similarities. The same instructional approach of deriving interacting cues can facilitate such overlooking. For example, in Study 2 of Chi et al. (1981), physics problems were intentionally designed so that they looked similar at the surface level (the diagram looked similar, the problem statement contained the same concepts and entities and described the same situations) but required

730 different deep principles for solutions. In fact, the entire description of the problem statement was identical with the exception of the final question. For example, both problems began with

735 A man of mass  $M_1$  lowers himself to the ground from a height  $X$  by holding onto a rope passed over a massless frictionless pulley and attached to another block of mass  $M_2$ . The mass of the man is greater than the mass of the block.

One problem then asked students to find *the tension on the rope* (thus making it into a force problem), whereas the other problem asked students to find *the speed* that the man hit the ground (making it an energy problem). Thus the two problems required very different underlying solution principles based on the question that was asked at the end. Experts treated these two problems as different (by sorting them into different categories) whereas novices treated them as the same. The puzzle is, How is it possible that experts can see a different deep structure when the surface features were essentially identical? That is, by what processes do experts "see" the deep structure? When an expert reads "find the tension in the rope," the expert considers the interaction of the surface cue "tension" with the gravitational force on the block, the mass of the block, and the acceleration of the block (i.e., Newton's Second Law applied to the block) and its interaction with the gravitational force on the man, the mass of the man and the acceleration of the man (i.e., Newton's Second Law applied to the man). On the other hand, when the expert reads "find the speed of the block when it hits the ground," the expert considers the interaction of the surface feature "speed" with the height of the block at ground level (which is zero), the mass of the block, and the total mechanical energy of the block (i.e., definition of mechanical energy applied to the block). In short, depending on which surface cue is in the "find . . ." statement, the expert notices different first-order cues for the whole solution.

735 To implement the instructional approach of teaching students about cues requires that researchers and instructional designers first elicit from experts the cues that they use, as opposed to our earlier focus on the principles that they used (Chi et al., 1981). Such a knowledge elicitation approach requires more than just collecting and *analyzing problem solving protocols*, as the protocols may not reveal the cues of the experts, because experts can perceive the derived cues for routine problems implicitly without explicitly mentioning or even consciously reasoning about them. Such an elicitation method is also different from merely asking domain experts for their *subjective opinions* on how to solve or how to instruct students to solve problems. Experts' subjective opinions can often be misleading. Although this instructional approach is domain specific in the sense that how experts derive cues must be known before instruction can be designed, the approach itself is applicable to multiple domains for which interaction cues must be derived in order for novice students to "see" the underlying structure.

#### Are First-Order Cues Sufficient for Transfer?

740 Having recommended teaching students more explicitly how to derive the first-order cues or quantities that relate the interaction of several surface features, the question now is whether successfully deriving the first-order cues is sufficient for transfer, and if not, what else is needed. Our conjecture is that transfer is based on second-order cues, where second-order cues are relations among first-order cues.

In our cart-ramp problem, once the first-order cues are derived (i.e., the energy at the initial time and the energy at the final time), learners need to infer that they are *equal*. This equality relates two first-order interactions, so it is a second-order cue. There are two ways to infer this second-order cue of equality: a top-down way and a bottom-up way. Experts would know that the Conservation of Total Mechanical Energy principle applies in this problem because there is no friction or heating. That is, the surface feature or condition of *no friction* elicits the Conservation of Total Mechanical Energy principle. And if this principle applies, this means that the second-order relationship of energies at the initial and final times is equal. However, we assume instead that naïve students have not understood this principle; that is, they have not learned that *no friction* is an important *condition* that should invoke the Conservation principle, which in turn dictates the *equality* of total energy at two time points. What they have learned basically is to associate an equation with the name of the principle. Thus, novice students cannot solve this problem in a top-down way.

This assumption that they have not learned all the conditions that invoke a principle is based on our prior analyses of novice students' self-explanations when they studied worked-out physics examples. From their self-explanations, we coded their acquisition of physics principles such as Newton's First and Second Laws (Chi & VanLehn, 1991, p. 94). We found that the acquisition of Newton's Second Law, for example, consisted of learning several unidirectional inference rules, each with specific conditions (including inducing an incorrect inference rule), such as

1. If the forces acting on a body do not sum to zero, then the body will move.
2. If a body is accelerating, then its net force must not be zero.
3. If a body has acceleration, then it must experience a net force.
4. If a body has a net force, then it is accelerating.
5. If a body is not at rest, then the net force will not equal to zero (incorrect).

This analysis suggests that learning a principle such as Newton's Second Law (that the sum of Forces =  $ma$ ) requires that students first acquire multiple unidirectional inference rules with various specific conditions. Although we surmise that experts treat all these inference rules as simple variations on a principle and know all the conditions that can elicit the correct principle, for novice students, complete understanding of the principle may require acquiring all the various unidirectional conditional rules related to the principle, weeding out incorrect unidirectional rules, then consolidating the remaining correct unidirectional rules into a single bidirectional principle (e.g.,  $F = ma$ ). In short, we assume that novice learners cannot readily invoke the correct principle (e.g., Conservation of Energy) from a condition stated in the problem statement (such as *no friction*), to then conclude

in a top-down way that the energies at the two time points are equal.

If novice students have not learned all the conditions that can invoke a relevant principle to apply, then how can they possibly transfer, as transfer is often based on "seeing" the deep principle? With respect to the cart-ramp problem, this means that after having derived the first-order cues of the mechanical energy at the initial and final times, how will novice students know that they should be equal?

We propose that there is a bottom-up way to learn the principle, and that is for novice learners to be taught to *notice* the second-order cues, which consist of simple relationships such as *equal to*, *greater-than*, *less-than*, and so on. Continuing with the previous example, suppose novices see how the problem was solved for the height of the ramp (the unknown quantity) by setting the two energies to be equal (such as from studying a work-out example); this allows them to compute the total mechanical energy at the two time points and therefore finding the unknown height quantity. Through such exercises, novices can *notice* that the two expressions are equal. Essentially the outcome of noticing is comparable to applying the Conservation of Energy principle. However, our bottom-up approach provides a way for students to learn to induce and transfer by the second-order relationship of *equality*, without assuming that they already know and can invoke the principle in a top-down way. In fact, we surmise that this bottom-up approach may be the route by which students eventually acquire an operational version of the Conservation of Total Mechanical Energy. Thus, this is a bottom-up approach, in contrast to the experts' top-down approach of applying a principle that is already known and invoked.

To recap, we are proposing that the difficulty for novice learners in transfer is not realizing that (a) they must derive first-order cues from the interactions of objects and entities directly stated in the problem, and then (b) they must look for and notice the second-order cues of equal to, or greater than, and so on. Our assumption is that "seeing" the second-order relationships is not difficult because the relationships are commonsense everyday ones, whereas first-order cues may involve complicated and unfamiliar interactions. Nevertheless, students must be told that they need to notice the second-order cues, after they have learned to derive the first-order cues.

We can provide another example to point out that the nature of second-order cues are familiar everyday relationships such as *simultaneous*, *independent*, *all*, and so on (Chi et al., 2012). For example, for many science concepts of processes taught in school, it is often mandatory for learning and correct understanding that students can understand an emergent kind of processes (such as *diffusion of ink in water*). One way to understand an emergent process is to notice a set of relevant second-order cues among the first-order interactions. For example, to understand *diffusion flow*, students have to notice that the collisions of molecules (a first-order interaction) can occur *simultaneously* (a second-order relationship). In other

change "processes" to "process"

words, one pair of molecules colliding can occur *simultaneously* with another pair of molecules colliding. Another second-order relationship is that the pairs of molecules can collide *independently* of each other pair's collisions. Again, we assert that the meaning of these second-order relationships (e.g., *simultaneous*, *independent*) themselves are not difficult to understand. The problem is that students need to be told to notice these second-order relationships, and to recognize that they are the same across situations or problems, thereby allowing them to transfer.

In sum, although deep structure in a problem can refer to both first-order and second-order cues, we propose that transfer is based on the second-order relationships. But second-order relationships can only be perceived when first-order interactions are derived. Therefore, instruction needs to focus on both deriving first-order interaction cues and noticing second-order relationships.

### Similarities and Differences With Analogies

The first-order types of cues described here in the context of learning to solve problems are similar to those described by Gentner (1983) in the context of solving analogy problems or understanding analogies such as "The atom is like the solar system." In this solar system example, the entities in a solar system are the planets and sun. The first-order relationships (statements about entities) are that the planets *revolve* around the sun and that the planets and the sun *attract* each other. The second order relationships (statements about statements) are that the attraction of the planets and the sun *causes* the revolution of the planets around the sun. Thus the second-order cue is a causal relationship, whereas in the case of the cart-ramp example, the second-order relationship is that of *equality* between the initial and final energy, so in both cases, we assert that the second-order relationships (causal or equivalent) are everyday relationships that students are familiar with and can understand. It is simply a matter of *noticing what they are*.

However, there are many differences between learning to solve problems (as in physics) and learning about atoms from analogizing to the solar system. First, the first-order interaction cues of the planet-solar analogy (revolving, attracting) are already known and familiar to students while learning about atoms, whereas students must learn to derive the first order relationship of mechanical energy at both time points.

A second difference between the planet-solar analogy example and the cart-ramp problem-solving example has to do with our assumption about transfer. In analogy, transfer is based on the success of mapping. As Gentner pointed out, when students are told, "The atom is like the solar system," making correct inferences about the atom requires that students realize not only that the electrons are like the planets and the nucleus is like the sun (mapping the entities) but also that they map over the first-order relationships (revolving, attracting) and the second-order relationships (attracting

causing revolving). We postulate instead that transfer in problem solving is not based on mapping either the entities or the first-order relationships, as they can be so different between problems, but rather transfer is based on noticing the similarity in the second-order relationships.

To illustrate the role of the second-order relationships on transfer in physics, consider the following problem:

A block of mass  $M$  is dropped onto a spring with a spring constant  $k$ . When the spring is fully compressed, the block is  $H$  meters below where it started. How much was the spring compressed? Neglect friction and heating of the spring.

To transfer the solution of the cart-ramp problem to this block-spring problem, students must notice that the energy at the initial time equals the energy at the final time for both problems (i.e., the second-order cues are the same for the two problems). From this example, we can see more clearly the differences between problem-solving transfer and analogy transfer. First, in analogy transfer, the nature of the first-order interactions are identical in order for transfer to occur (both situations involve *revolving* or *attracting*), whereas the first-order interactions are not identical in the case of the physics problems; that is, the way energy is computed in the cart-ramp case is quite different from the way energy is computed in the block-spring case. The cart case involves the interaction of the cart's velocity, mass, and height, whereas the spring case involves computing the interaction between the blocks' velocity, the spring's compression distance and its spring constant.

A second difference between the analogy of the solar system to the atom and the analogy of the cart-ramp system to the block-spring system is that the solar system is more explicitly taught and thus better understood than the artificially constructed cart-ramp situation. Thus, the solar system is often used to teach students about the atom because students have explicitly been taught the solar system's first-order relationship (attracting, revolving) and second-order relationship (attracting cause revolving). In the case of problem solving in physics, and the cart-ramp problem as an example, students are taught a mathematical derivation of its solution but they are not explicitly taught how they need not only to derive the first-order interactions but also to notice the second-order relationships. Thus, students are not able to use the cart-ramp problem to understand how to solve the block-spring problem.

In this article, we present the novel hypothesis that one reason transfer often fails in the two-problem transfer paradigm is that students have not learned to derive deeper first-order cues from attending to the interactions of the surface features, and notice the relationships between the first-order interactions

infinitive verb-agreement -  
add "to" before "students"

delete comma

insert comma

insert "in"  
before  
"the" -USION

1025 (i.e., the second-order cues). Based on this hypothesis, we  
 propose an instructional approach that focuses on explicitly  
 teaching students how to derive first-order interaction cues  
 and notice second-order relationships. We showed how such  
 cues could be useful in learning to transfer when the surface  
 1030 features are different but the deep structures of second-order  
 cues are the same, and conversely in preventing students  
 from being misled by situations where the surface features  
 are predominately similar but in fact the deep structures are  
 different. Although most methods of teaching for transfer  
 1035 mention surface features and deep structures, we advocate  
 instruction to focus on deriving first-order cues. Because  
 both the first-order and second-order cues can be inferred  
 from percepts, they explain the dilemma of understanding  
 how experts can “see” the deep structures from the same  
 1040 surface features available to novices.

Our instructional proposal can be characterized as more  
 of a bottom-up approach. It is bottom-up in that it focuses on  
 teaching students how to derive interaction cues and to notice  
 second-order relationships between the first-order interac-  
 1045 tion cues. Once these second-order relationships are noticed,  
 learners can then apply more straightforwardly the relevant  
 equations or principles. Deriving these cues and noticing  
 their relationships characterize what we believe is the skill of  
 “seeing” the underlying structure.

1050 This bottom-up approach is different from the assump-  
 tions of a typical top-down approach. A top-down approach  
 takes the perspective of the experts and assumes, for the  
 problem just described, that success is determined by already  
 knowing the principle, which is invoked from specific surface  
 1055 features, such as that *friction is zero implies that the Conser-  
 vation of Total Mechanical Energy principle applies (thereby  
 the energies at the two points are equal)*. However, we have  
 shown that novice students, even those who have received a  
 grade of B or better, have not yet acquired a complete under-  
 1060 standing of the principles. As we previously described, this  
 can be seen by two kinds of evidence: first, in their incom-  
 plete acquisition of unidirectional conditional rules related to  
 the Second Law (including the acquisition of incorrect condi-  
 tional rule), and second, in their incomplete articulation of all  
 1065 the components of a principle (missing especially the compo-  
 nents related to interactions of the Third Law). Such evidence  
 suggests that even after having the opportunity to learn the  
 relevant materials (such as Chapter 5 of Halliday & Resnick,  
 1974) or having completed a course on mechanics, students  
 1070 did not have complete understanding of the principles em-  
 bedded in the chapter. Therefore, a bottom-up approach of  
 first learning to derive the first-order interaction cues fol-  
 lowed by noticing second-order relationships, may lead to  
 transfer and subsequently to a more complete understanding  
 1075 of the relevant principle. Thus, we are suggesting that deep  
 structure may be the second-order relationships between the  
 first-order derived cues.

Although the examples used in this article to illustrate our  
 interaction hypothesis focus on the domain of physics, we

believe that this approach is generalizable to other domains as 1080  
 well. That is, in many other domains, it is also the first-order  
 and the second-order cues that must be derived and attended  
 to in order to understand problems, analogies, or processes  
 correctly. We illustrated the importance of first- and second-  
 1085 order cues in physics problems, in scientific analogies, and  
 in understanding emergent processes.

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# Teaching the Conceptual Structure of Mathematics

Lindsey E. Richland, James W. Stigler, and Keith J. Holyoak

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## Teaching the Conceptual Structure of Mathematics

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Many students graduate from K–12 mathematics programs without flexible, conceptual mathematics knowledge. This article reviews psychological and educational research to propose that refining K–12 classroom instruction such that students draw connections through relational comparisons may enhance their long-term ability to transfer and engage with mathematics as a meaningful system. We begin by examining the mathematical knowledge of students in one community college, reviewing results that show even after completing a K–12 required mathematics sequence, these students were unlikely to flexibly reason about mathematics. Rather than drawing relationships between presented problems or inferences about the representations, students preferred to attempt previously memorized (often incorrect) procedures (Givvin, Stigler, & Thompson, 2011; Stigler, Givvin, & Thompson, 2010). We next describe the relations between the cognition of flexible, comparative reasoning and experimentally derived strategies for supporting students' ability to make these connections. A cross-cultural study found that U.S. teachers currently use these strategies much less frequently than their international counterparts (Hiebert et al., 2003; Richland, Zur, & Holyoak, 2007), suggesting that these practices may be correlated with high student performance. Finally, we articulate a research agenda for improving and studying pedagogical practices for fostering students' relational thinking about mathematics.

Many schools are failing to teach their students the conceptual basis for understanding mathematics that could support flexible transfer and generalization. Nowhere is this lack of a conceptual base for mathematical knowledge more apparent than among the population of American students who have successfully graduated from high school and entered the U.S. community college system (Givvin, Stigler, & Thompson, 2011; Stigler, Givvin, & Thompson, 2010). These community college students have completed the full requirements of a K–12 education in the United States and made the motivated choice to seek higher education, but typically without the financial resources or academic scores to enter a 4-year institution. Despite having completed high school successfully, based on entry measures the majority of these stu-

dents place into “developmental” or “remedial” mathematics courses (e.g., Adelman, 1985; Bailey, Jenkins, & Leinbach, 2005). Too often, these remedial courses then turn into barriers that impede progress toward a higher level degree (Bailey, 2009).

The numbers of community college students in the United States who cannot perform adequately on basic mathematics assessments provides some insight into the questionable efficacy of the U.S. school system. More broadly, detailed measures of these students' knowledge further elucidate the ways in which K–12 educational systems (in any country) have the potential to misdirect the mathematical thinking of many students. We begin this article by describing the results of detailed assessment and interview data from students in a California community college to better understand some longer term outcomes of a well-studied K–12 educational system (Givvin et al., 2011; Stigler et al., 2010). To anticipate, the mathematics knowledge of these students appears

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to be largely bound to specific procedures, leaving the students ineffective at reasoning through a mathematics problem. They are apt to attempt procedures that are partially or incorrectly recalled without regard to the reasonableness of the solution.

We then consider what may be missing from typical U.S. K–12 mathematics instruction, a gap that leads to such impoverished knowledge representations. In particular, we consider one key to developing flexible and conceptual understanding: comparing representations and drawing connections between them. This topic has been the focus of a great deal of cognitive and educational research, enabling us to forge relationships between these literatures to draw implications for pedagogical practice. An integration of these literatures leads us to posit the crucial roles of developing causal structure in knowledge representations, and in supporting students in learning to represent novel problems as *goal-oriented structured systems*.

The term “conceptual understanding” has been given many meanings, which in turn has contributed to difficulty in changing teacher practices (e.g., see Skemp, 1976). For our purposes in this article, we rely on a framework proposed by Hatano and Inagaki (1986), which characterizes conceptual understanding as attainment of an expertlike fluency with the conceptual structure of a domain. This level of understanding allows learners to think generatively within that content area, enabling them to select appropriate procedures for each step when solving new problems, make predictions about the structure of solutions, and construct new understandings and problem-solving strategies. For the sake of clarity, rather than discussing “conceptual understanding” throughout his article, we primarily focus our review of the literature and research agenda on the goal of facilitating learners’ acquisition of the *conceptual structure* of mathematics.

We next turn from consideration of student knowledge to studies of videotaped teacher practice, to examine the alignment between current teacher practice and the strategies we hypothesize to be effective. We find that the practices of American teachers often do not correspond at all well with the strategies that we believe would promote deep learning and acquisition of the conceptual structure of mathematics. Finally, we consider the role that researchers can play in understanding how teachers might practicably engage students in effective representational thinking. We lay out a research agenda with the aim of developing strategies for facilitating students’ learning to reason about mathematics and to generalize their mathematical knowledge.

## WHAT COMMUNITY COLLEGE STUDENTS KNOW ABOUT MATHEMATICS

Studying the U.S. mathematics instructional system provides insights into more general relationships between student knowledge, student cognition, and teacher practices. We

know from international research that American students fall far behind their counterparts in other industrialized nations, both on standardized tests of mathematics achievement (Gonzales et al., 2008) and on tests designed to measure students’ abilities to apply their knowledge to solving novel and challenging problems (Fleishman, Hopstock, Pelczar, & Shelley, 2010). We also know that the gap between U.S. students and those in other countries grows wider as students progress through school, from elementary school through graduation from high school (Gonzales et al., 2008).

Many researchers have attributed this low performance in large part to the mainly procedural nature of the instruction American students are exposed to in school (e.g., Stigler & Hiebert, 1999). By asking students to remember procedures but not to understand when or why to use them or link them to core mathematical concepts, we may be leading our students away from the ability to use mathematics in future careers. Perhaps nowhere are the results of our K–12 education system more visible than in community colleges. As previously noted, the vast majority of students entering community college are not prepared to enroll in a college-level mathematics class (Bailey, 2009). We know this, mostly, from their performance on placement tests. But placement tests provide only a specific type of information: They measure students’ ability to apply procedural skills to solving routine problems but provide little insight into what students actually understand about fundamental mathematics concepts or the degree to which their procedural skills are connected to understandings of mathematics concepts.

American community college students are interesting because they provide a window for examining long-term consequences of a well-studied K–12 instructional system. Not everyone goes to community college, of course. Some students do not continue their education beyond the secondary level, and some American students, through some combination of good teaching, natural intelligence, and diligent study, learn mathematics well in high school and directly enter 4-year colleges. Some community college students pass the placement tests and go on to 4-year colleges, and some even become mathematicians. However, we believe much can be learned from examining the mathematical knowledge of that majority of community college students who place into developmental mathematics courses. Most of these students graduated high school. They were able to remember mathematical procedures well enough to pass the tests in middle school and high school. But after they stop taking mathematics in school, we can see what happens to their knowledge—how it degrades over time, or perhaps was never fully acquired in the first place. The level of usable knowledge available to community college students may tell us something about the long-term impact of the kinds of instructional experiences they were offered in their prior schooling.

We begin by looking more closely at what developmental mathematics students in community college know and understand about mathematics. Little is known about the

165 mathematical knowledge of these students. Most of what  
we know was learned in two small studies—one a survey  
of several hundred students at one Los Angeles area col-  
lege (Stigler et al., 2010), and the other a more qualitative  
170 interview study in which interviewers engaged students in  
conversations about mathematics (Givvin et al., 2011). Both  
of these studies steered clear of the typical, procedural ques-  
tions asked on placement tests. Students were not asked to  
multiply fractions, perform long division, or solve algebraic  
equations. The questions focused instead on very basic con-  
175 cepts: Could students, for example, place a proper fraction  
on a number line, or use algebraic notation (e.g.,  $a + b = c$ )  
to reason about quantitative relationships? More general  
questions were also asked, such as, What does it mean to do  
180 mathematics? We briefly summarize some of the conclusions  
from these two studies.

change "W" in "what" to lowercase.

### Students View Mathematics as a Collection of Rules and Procedures to Be Remembered

185 Consistent with the view that K–12 mathematics instruction  
focuses primarily on practicing procedures, these students for  
the most part have come to believe that mathematics is not  
a body of knowledge that makes sense and can be “figured  
out.” Instead, they see mathematics as a collection of rules,  
procedures, and facts that must be remembered—a task that  
gets increasingly more difficult as students progress through  
190 the curriculum.

When asked what it means to be “good at mathematics,”  
77% of students presented views consistent with these beliefs  
(Givvin et al., 2011). Here is a sampling of what they said:

- “Math is just all these steps.”
- 195 • “In math, sometimes you have to just accept that that’s the  
way it is and there’s no reason behind it.”
- “I don’t think [being good at math] has anything to do  
with reasoning. It’s all memorization.”

200 This is, of course, a dysfunctional view of what it means to  
do mathematics. If students don’t believe that it is possible to  
reason through a mathematics problem, then they are unlikely  
to try. And if they don’t try to reason, to connect problems  
with concepts and procedures, then it is hard to imagine how  
they would get very far in mathematics.

205 Mathematicians, naturally, see reasoning about relation-  
ships as central to the mathematical enterprise (e.g., Hilbert,  
1900; Polya, 1954), a view that also is common among math-  
ematics teachers at community colleges. When data on stu-  
dents’ views of mathematics were presented to a community  
210 college mathematics department, the faculty members were  
astounded. One said, “The main reason I majored in mathe-  
matics was because I didn’t have to memorize it, it could all be  
figured out. I think I was too lazy to go into a field where you  
had to remember everything.” Every one of the other faculty  
215 members present immediately voiced their agreement.

Given this disconnect between the students and their com-  
munity college professors, one might ask where the students’  
views of mathematics come from, if not from their teachers?  
First, it is important to point out that they bring this view with  
them based on their K–12 experiences. But it also is quite 220  
possible that students’ views of what it means to do mathe-  
matics arise not from the beliefs of their teachers but from  
the daily routines that define the practice of school mathe-  
matics (see, e.g., Stigler & Hiebert, 1999). Unless teachers’  
beliefs are somehow instantiated in daily instructional rou- 225  
tines or made explicit in some other way, they are unlikely to  
be communicated to students.

As we see later, the routines of K–12 school mathematics  
emphasize repeated recall and performance of routine facts  
and procedures, and these routines are supported by state 230  
standards, assessments, and textbooks in addition to teaching  
practices. Although a small percentage of students do seek  
meaning and do achieve an understanding that is grounded  
in the conceptual structure of mathematics—and we assume  
that community college mathematics faculty are among this 235  
small percentage—the majority of students appear to exit  
high school with a more limited view of what it means to do  
mathematics.

### Regardless of Placement, Students Are Lacking Fundamental Concepts That Would Be Required to Reason About Mathematics 240

Although the developmental mathematics students in the  
studies were placed into three different levels of mathe-  
matics courses—basic arithmetic, pre-algebra, or beginning  
algebra—they differed very little in their understanding 245  
of fundamental mathematics concepts. Their similarity  
may not be that surprising given their procedural view of  
mathematics: If mathematics is not supposed to make sense,  
consisting mainly of rules and procedures that must be  
memorized, then basic concepts may not be perceived as 250  
useful. That said, the range of things these students did not  
understand is surprising.

One student, in the interviews, was asked to place the frac-  
tion  $4/5$  on a number line. He carefully marked off a line, la-  
beled the marks from 0 to 8, and then put  $4/5$  between 4 and 5. 255  
Many students appeared to have fundamental misunderstand-  
ings of fractions and decimals, not seeing them as numbers  
that could be compared and ordered with whole numbers. In  
the survey, students were shown the number line depicted in  
Figure 1, which spanned a range from  $-2$  to  $+2$ . They were 260  
asked to place the numbers  $-0.7$  and  $13/8$  on the number  
line. Only 21% of the students could do so successfully.

Most young children know that if you add two quantities  
together to get a third, the third quantity is then composed of  
the original two quantities such that if you removed one you 265  
would be left with the other. The students in these studies,  
however, seemed happy to carry out their mathematics work  
without connecting it to such basic ideas. In the interviews

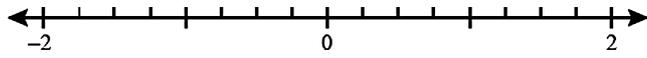


FIGURE 1 Number line on which students were to place  $-.7$  and  $13/8$ . From "What Community College Developmental Mathematics Students Understand About Mathematics," by J. W. Stigler, K. B. Givvin, and B. Thompson, 2010, *The MathAMATYC Educator*, 10. Copyright 2010 by American Mathematical Association of Two-Year Colleges. Reprinted with permission.

Q2

270 a student was asked if he could think of a way to check that  
the sum of two three-digit numbers was correct. The spe-  
cific example presented was  $462 + 253 = 715$ . The student  
proceeded to subtract 253 from 715 and ended up with 462.  
The interviewer then asked him if he could have subtracted  
the 462 instead. He did not think so; he had been told, he  
275 said, that you subtract the second addend, not the first. But  
would it make a difference, the interviewer asked? He wasn't  
sure. The interviewer told him he could try it, and he did.  
He seemed genuinely surprised to find that, indeed, he could  
subtract either addend to get the other.

280 In one final example, students were asked, "Which is  
greater?  $a/5$  or  $a/8$ . Only 53% correctly answered  $a/5$ , a  
percentage that could have been obtained just by guessing.  
The students were also asked to explain how they got their  
answer. About one third (36%) could not come up with  
285 an explanation (half of these had answered correctly, the  
other half incorrectly). The ones who provided some sort  
of explanation tended to summon some rule or procedure  
from memory that they thought might do the trick. Many  
of the students said that  $a/8$  is larger because 8 is larger  
290 than 5. Not surprisingly, another group claimed just the  
opposite, having remembered that the lower the denominator  
the larger the number. Some students tried to perform a  
procedure: Some found common denominators, though  
often they made mistakes and got the wrong answer anyway.  
295 Others cross-multiplied (something they apparently believed  
you can do whenever you have two fractions).

Only 15% of the students tried to reason it through. These  
students said things such as, If you have the same quantity  
and divide it into five parts, then the parts would be larger  
than if you divide it into eight parts. Assuming you have the  
same number of these different-sized parts, then  $a/5$  must  
be larger. Although it is discouraging that only 15% took  
this approach, it is interesting to note that every one of these  
300 students got the answer correct. If we could only figure out  
how to connect such fundamental ideas with the mathematics  
procedures students are learning in school, the mathematical  
knowledge the students acquire might be more robust.

add quotes around "If you have the same... etc"

310 Students Almost Always Apply Standard Procedures, Regardless of Whether They Make Sense or Are Necessary

Students were asked a number of questions in the interviews that could have been answered just by thinking. As evident in

the preceding example, only a small percentage of students tried to think their way to a solution. For some questions, just a bit of thinking and reflection might have guided students 315 to use a more appropriate procedure, or to spot errors in the procedures they did use. Rarely, however, did students take the bait.

In one part of the interview students were presented with a list of multiplication problems and asked to solve them 320 mentally:

- $10 \times 3 =$
- $10 \times 13 =$
- $20 \times 13 =$
- $30 \times 13 =$
- $31 \times 13 =$
- $29 \times 13 =$
- $22 \times 13 =$

Clearly there are many relationships across these problems, and results of previous problems could potentially be used to derive the answers to subsequent problems. But this was not the way in which students approached this task. 325 Most students just chugged through the list, struggling to apply the standard multiplication algorithm to each problem. Fully 77% of the students never noticed or used any relation among the different problems, preferring to work each problem independently. 330

Here is an example of the answers produced by one student (Givvin et al., 2011):

- $10 \times 3 = 30$
- $10 \times 13 = 130$
- $20 \times 13 = 86$
- $30 \times 13 = 120$
- $31 \times 13 = 123$
- $29 \times 13 = 116$
- $22 \times 13 = 92$

In summary, most students answered most problems by retrieving answers or procedures from memory. Many of the procedures they used were not necessary or not appropriate 335 to the problem at hand. Rarely were the procedures linked to concepts, which might have guided their use in more appropriate ways. When students were asked to solve multiple problems they almost never made comparisons across the problems, leading to more mistakes and fewer opportunities 340 to infer the principles and concepts that could make their knowledge more stable, coherent, flexible, and usable.

insert comma

delete comma

345 Why might students have developed such an orientation toward mathematics through their K–12 mathematics education? Although teaching in the United States is multifaceted and the reasons behind student success or failure are much too complex to fully treat here, we consider in particular one candidate explanation: Students do not view mathematics as a *system*, because their teachers do not capitalize on opportunities to draw connections between mathematical representations. In the following sections we first expand on what kinds of processes might be required for the development of deep and flexible mathematical knowledge. We then consider, based on classroom observational studies, whether American students have opportunities to engage in these processes. We first consider the cognition involved in students' comparative thinking and transfer, and then we turn to studies of teacher practices to examine alignment between pedagogy and cognition.

360 LEARNING RELATIONAL STRUCTURE THROUGH COMPARISON

It seems a safe conjecture that the very same students who apparently found no interesting patterns within a series of juxtaposed multiplications by 13 are quite capable of noticing other sorts of potential comparisons and learning from them. They might compare the plots of movies, the sources of difficulty in different video games, the reasons why various romantic relationships have succeeded or failed. In such everyday situations people of all ages, including the very young, spontaneously seek explanations for *why* things happen, especially when faced with surprising events (e.g., Legare, Gelman, & Wellman, 2010). The answer to a “why” question inevitably hinges on relational representations, particularly *cause–effect* relations (for a review, see Holyoak & Cheng, 2011), or more generally (and especially in mathematics), *functional* relations that govern whether inferences are justified (Bartha, 2010).

add "the age of" before "13" to clarify

Learning Schemas Via Analogical Reasoning

380 A causal model is a kind of *schema*, or mental representation of the relational structure that characterizes a class of situations. The acquisition of schemas is closely related to the ability to compare situations and draw *analogies* based in part on corresponding relations. Analogical reasoning is the process of identifying goal-relevant similarities between what is typically a familiar *source* analog and a novel, less understood *target*, and then using the set of correspondences, or *mapping*, between the two analogs to generate plausible inferences about the latter (see Holyoak, 2012, for a review). The source may be a concrete object (e.g., a balance scale), a set of multiple cases (e.g., multiple problems involving balancing equations), or a more abstract schema (e.g., balancing equations in general). The target

may be a relatively similar problem context (e.g., a balancing equations problem with additional steps), or a more remote analog (e.g., solving a proportion). 395

It has been argued that analogical reasoning is at the core of what is unique about human intelligence (Penn, Holyoak, & Povinelli, 2008). The rudiments of analogical reasoning with causal relations appear in infancy (Chen, Sanchez, & Campbell, 1997), and children's analogical ability becomes more sophisticated over the course of cognitive development (Brown, Kane, & Echols, 1986; Holyoak, Junn, & Billman, 1984; Richland, Morrison, & Holyoak, 2006). Whereas very young children focus on global similarities of objects, older children attend to specific dimensions of variation (Smith, 1989) and to relations between objects (Gentner & Rattermann, 1991). 400 405

Analogical reasoning is closely related to transfer. Crucially, comparison of multiple analogs can result not only in transfer of knowledge from a specific source analog to a target (Gick & Holyoak, 1980) but also in the induction of a more general schema that can in turn facilitate subsequent transfer to additional cases (Gick & Holyoak, 1983). People often form schemas simply as a side effect of applying one solved source problem to an unsolved target problem (Novick & Holyoak, 1991; Ross & Kennedy, 1989). The induction of such schemas has been demonstrated both in adults and in young children (e.g., Brown et al., 1986; Chen & Daehler, 1989; Holyoak et al., 1984; Loewenstein & Gentner, 2001). Comparison may play a key role in children's learning of basic relations (e.g., comparative adjectives such as “bigger than”) from nonrelational inputs (Doumas, Hummel, & Sandhofer, 2008), and in language learning more generally (Gentner & Namy, 2006). Although two examples can suffice to establish a useful schema, people are able to incrementally develop increasingly abstract schemas as additional examples are provided (Brown et al., 1986; Brown, Kane, & Long, 1989; Catrambone & Holyoak, 1989). 410 415 Q3 420 425

Why Schema Learning Can Be Hard (Especially in Mathematics) 430

If humans have a propensity to use analogical reasoning to compare situations and induce more general schemas, why did the community college students described earlier appear not to have acquired flexible schemas for mathematical concepts? Several issues deserve to be highlighted. As we have emphasized, most everyday thinking focuses on understanding the physical and social environment, for which causal relations are central (Holyoak, Lee, & Lu, 2010; Lee & Holyoak, 2008). Not all relational correspondences are viewed as equally important. Rather, correspondences between elements causally related to a reasoning goal are typically considered central (Holyoak, 1985; Spellman & Holyoak, 1996). It seems that the human ability to learn from analogical comparisons is closely linked to our tendency to 435 440

445 focus on cause–effect relations, which are the building blocks  
of causal models.

But by its very nature, mathematics is a formal system,  
within which the key relations are not “causal” in any straight-  
forward sense. (Note that this observation applies not only  
450 to mathematics but to other domains as well. For example, a  
similar pattern of teaching and learning has been identified  
in the domain of physics by Jonassen, 2010.) Worse, unless  
mathematical procedures are given a meaningful interpreta-  
tion, students may assume (as we  
455 no real “reasons” why the procedures work. In some sense,  
the community college students we interviewed probably did  
have a “schema” for multiplication, consisting of roles for  
multiplicands and a product. However, lacking any mean-  
ingful model of what multiplication “means” outside of the  
460 procedure itself, the students lacked a reliable basis for find-  
ing “interesting” relationships between juxtaposed problems  
such as “ $10 \times 13 =$ ” and “ $20 \times 13 =$ ”.

In contrast, their community college professors clearly  
viewed mathematics as a *meaningful* system, governed by an  
interconnected set of relations. Though not “causal” per se,  
465 these relations are seen as having *relevance* to mathematical  
goals (Bartha, 2010). As Bartha argued, the general notion of  
functional relevance (of which causal relations are a special  
case) governs inference based on mathematics. Just as causal  
relations determine the consequences of actions in the phys-  
ical world, mathematical relations determine the validity of  
470 procedures in a formal world. For example, multiplication  
can be defined as repeated addition, which can be defined  
in turn as the concatenation of two quantities, and quantities  
can in turn be decomposed (e.g., the quantity 20 is equal to  
two quantities of 10). This is the type of relational knowl-  
edge required to notice, for example, that the value of  $20 \times$   
13 has a special relationship to the value of  $10 \times 13$ . Simi-  
larly, the professors, but not their students, understand that  
480 numbers in decimal notation like  $-0.7$  and improper fractions  
like  $13/8$ , along with integers, can all be placed on a num-  
ber line because all of them are real numbers, representing  
quantities along a continuum. One might say, then, that the  
students and their professors have incommensurate schemas  
485 for mathematics, in that only the latter place emphasis on  
functional relations that serve to explain why various math-  
ematical inferences are valid.

Clearly, simply solving sequences of math problems is no  
guarantee that the student will end up deeply understanding  
490 the conceptual structure of mathematics. Even in nonmath-  
ematical domains, simply providing multiple examples does  
not ensure formation of a useful schema. If two examples are  
juxtaposed but processed independently, without relational  
comparison, learning is severely limited (Gentner, Loewen-  
stein, & Thompson, 2003; Loewenstein, Thompson, & Gen-  
tner, 2003). Even when comparison is strongly encouraged,  
495 some people will fail to focus on the goal-relevant functional  
relations and subsequently fail on transfer tasks (Gick &

Holyoak, 1983). When mathematics problems are embedded  
in specific contexts, details shared by different contexts are  
500 likely to end up attached to the learned procedure, potentially  
limiting its generality. For example, people tend to view ad-  
dition as an operation that is used to combine categories at  
the same level in a semantic hierarchy (e.g., apples and or-  
anges, not apples and baskets; Bassok, Pedigo, & Oskarsson,  
505 2008), because word problems given in textbooks always re-  
spect this constraint. At an even more basic level, analogical  
transfer is ultimately limited by the reasoner’s understanding  
of the source analog (Bartha, 2010; Holyoak et al., 2010). If  
every solution to a math problem is viewed as “just all these  
510 steps” with “no reason behind it,” simply comparing multiple  
examples of problems (that to the student are meaningless)  
will not suffice to generate a deep schema.

Thus, although relational comparisons can in principle  
foster induction of flexible mathematical knowledge, many  
515 pitfalls loom large. The teacher needs to introduce source  
analogues that “ground out” formal mathematical operations  
in domains that provide a clear semantic interpretation (e.g.,  
introducing the number line as a basic model for concepts  
and operations involving continuous quantities). Moreover,  
520 even if a good source analog is provided, relational com-  
parisons tax limited working memory (Halford, 1993; Hummer  
& Holyoak, 1997, 2003; Waltz, Lau, Grewal, & Holyoak,  
2000). In general, any kind of intervention that reduces  
525 working-memory demands, and helps people focus on goal-  
relevant relations, will aid learning of effective problem  
schemas and thereby improve subsequent transfer to new  
problems.

For example, Gick and Holyoak (1983) found that in-  
duction of a schema from two disparate analogs was facil-  
530 itated when each analog included a clear statement of the  
underlying solution principle. In some circumstances, trans-  
fer can also be improved by having the reasoner generate a  
problem analogous to an initial example (Bernardo, 2001).  
Other work has shown that abstract diagrams that highlight  
535 the basic solution principle can aid in schema induction and  
subsequent transfer (Beveridge & Parkins, 1987; Gick &  
Holyoak, 1983). Schema induction can also be encouraged  
by a procedure termed “progressive alignment”: providing  
a series of comparisons ordered “easy to hard,” where the  
540 early pairs share salient similarities between mapped objects  
as well as less salient relational correspondences (Kotovsky  
& Gentner, 2008). More generally, to understand the poten-  
545 tial role of analogical reasoning in education, it is essential  
to consider pedagogical strategies for supporting relational rep-  
resentations and comparative thinking. Next we consider sev-  
eral such pedagogical strategies, including highlighting goal-  
relevant relations in the source analog, introducing multiple  
550 source representations, and using explicit verbal and gestural  
cues to draw attention to relational commonalities and differ-  
ences (see also Schwartz, 2012/this issue, and Chi, 2012/this  
issue).

How American Teachers Introduce Mathematical Relations

555 Are teachers invoking these and related strategies in U.S. mathematics instruction, either explicitly or implicitly? Although the list of potential “best practices” in mathematics is long and varied, there is general agreement about the importance of drawing connections and supporting student reasoning. The National Council of Teachers of Mathematics (NCTM) has issued strong recommendations in this vein, publishing a new series of books for high school mathematics under the titled theme of *Reasoning and Sense-Making* (NCTM, 2009). They define “reasoning” broadly, including any circumstance in which logical conclusions are drawn on the basis of evidence or stated assumptions, from informal explanations to deductive and inductive conclusions and formal proofs (p. 19). Sense making is characterized as the interrelated but more informal process of developing understanding of a situation, context, or concept by connecting it with existing knowledge (p. 19). Based on reviews of educational research in mathematics and mathematics education, the authors explore the following theme throughout the main volume in this series as well as in books with specific curriculum foci:

Reasoning and sense making are the cornerstones of mathematics. Restructuring the high school mathematics program around them enhances students’ development of both the content and process knowledge they need to be successful in their continuing study of mathematics and in their lives. (p. 19)

These themes, though under the different title of “Focal Topics in Mathematics” are also central to their description of high quality elementary instruction (NCTM, 2006).

Thus, there is growing consensus in both the psychological and educational research literatures that teaching students effectively requires teaching them to reason with mathematics. Further, there is agreement that this aim necessitates drawing connections and fostering students’ awareness that mathematics is a sensible system, one that can be approached using the student’s broad repertoire of “sense making,” including causal and analogical thinking strategies. Approaching mathematics in this way enables students to develop better structured knowledge representations that may be more easily remembered and used more flexibly in transfer contexts—to solve novel problems, to notice mathematically relevant commonalities and differences between representations, and to reason through mathematics problems when one cannot remember a procedure.

Although drawing connections and sense making do not guarantee transfer, these are cognitive routines that lead to schema acquisition and knowledge representations that support transfer. Positive transfer will be facilitated by noticing similarities between two or more representations or objects.

INTERNATIONAL VARIATIONS IN STUDENTS’ OPPORTUNITIES FOR LEARNING TO DRAW CONNECTIONS IN MATHEMATICS

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Hiebert and Grouws (2007) conducted a meta-analysis of all studies in which features of teaching were empirically related to measures of students’ learning. They found that two broad features of instruction have been shown to promote students’ understanding of the conceptual structure of mathematics. First, teachers and students must attend explicitly to concepts, “treating mathematical connections in an explicit and public way” (p. 384). According to Hiebert and Grouws, this could include

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discussing the mathematical meaning underlying procedures, asking questions about how different solution strategies are similar to and different from each other, considering the ways in which mathematical problems build on each other or are special (or general) cases of each other, attending to the relationships among mathematical ideas, and reminding students about the main point of the lesson and how this point fits within the current sequence of lessons and ideas. (p. 384)

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The second feature associated with students’ understanding of mathematics’ conceptual structure is *struggle*: Students must spend part of each lesson struggling to make sense of important mathematics. Hiebert and Grouws defined “struggle” to mean “students expend effort to make sense of mathematics, to figure out something that is not immediately apparent” (p. 387). Thus, students must expend effort to make connections between the concepts and procedures that solve them. Note that Hiebert and Grouws point out that there is no single strategy for achieving these goals in classrooms, pointing out that there are many ways to do so. And clearly, not all struggle is good. One feature of the struggle they made is simply that connections are made *by the student* (i.e., they cannot be made by the teacher) and the making of these connections is a *part* of the lesson.

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change "students' " to "student's" --- subject-number agreement - "by the student" is singular in the beginning of the sentence, but it is plural here.

Corroboration of these conclusions comes from the largest studies ever conducted in which mathematics classrooms have been videotaped in different countries, the TIMSS video studies. Two studies were conducted: the first in 1995 in Germany, Japan, and the United States (Stigler & Hiebert, 1999), and the second in 1999 in seven countries: Australia, the Czech Republic, Hong Kong, Japan, the Netherlands, Switzerland, and the United States (Gonzales et al., 2008; Hiebert et al., 2003). In each country, a national probability sample of approximately 100 teachers was videotaped teaching a single classroom mathematics lesson. An international team of researchers collaboratively developed and reliably coded all lessons to gather data about average teaching practices across and within countries.

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tense agreement, study happened in the past, so the verbs should be in the past tense - change "are" to "were" here and before "worked"

655 One goal of these studies was to try to find features of teaching that might differentiate the high-achieving countries (in general, all except the United States and Australia in the preceding list) from the low-achieving countries. Of interest, the findings fit nicely with the conclusions of Hiebert and Grouws (2007), and also help to explain why we see the kind of outcomes just reported in the studies of community college developmental mathematics students. Many surface features of teaching did not appear associated with cross-national differences in student achievement. For example, among the high-achieving countries, there were countries that emphasized teacher lecture as the primary mode of instruction, and countries that tended to have students work independently or in groups on learning assignments. There were countries that used many real-world problems in their mathematics classes,

delete comma

most completely with symbolic simple variations could explain

tense agreement - change to "created"

675 Finding common features among the high-achieving countries required looking more closely at what was happening in the lessons. It was neither the kinds of problems presented nor teaching style employed that differentiated the high-achieving countries from the others, but the kinds of learning opportunities teachers create for students, namely, making explicit connections in the lesson among mathematics procedures, problems, and concepts and finding ways to engage students in the kind of productive struggle that is required to understand these connections in a deep way. The ways that teachers went about creating these learning opportunities differed from country to country. Indeed, an instructional move that inspires a Japanese student to engage might not have the same effect on a Czech student, and vice versa, due to the different motivational beliefs, attitudes, interests, and expectations students in different cultures bring

to the task at hand. But the quality of the learning opportunities teachers were able to create did seem to be common across the high-achieving countries.

This conclusion was based on an analysis of the types of problems that are presented, and how they are worked on, in different countries. Across all countries, students spend about 80% of their time in mathematics class working on problems, whether independently, as part of a small group, or as part of the whole class. The beginning and end of each problem was identified as it was presented and worked on in the videos. The types of problems presented were characterized, as was how each was worked on during the lesson.

The two most common types of problems presented were categorized as Using Procedures and Making Connections. Using Procedures problems, by far the most common across all countries, involved asking a student to solve a problem that they already had been taught to solve, applying a procedure they had been taught to perform. This is what is typically regarded as "practice." Take, for example, a lesson to teach students how to calculate the interior angles of a polygon. If the teacher has presented the formula  $[180 \times (\text{number of sides} - 2)]$ , and then asks students to apply the formula to calculate the sums of the interior angles of five polygons, that would be coded as Using Procedures. If, however, a teacher asks students to figure out why the formula works, to derive the formula on their own, or to prove that the formula would work for any polygon, that would be coded as a Making Connections problem. A problem like this has the potential for both struggle and for connecting students with explicit mathematical concepts.

The percentage of problems presented in each country that were coded as Using Procedures versus Making Connections is presented in Figure 2. As is evident in the figure, there was great variability across countries in the percentage

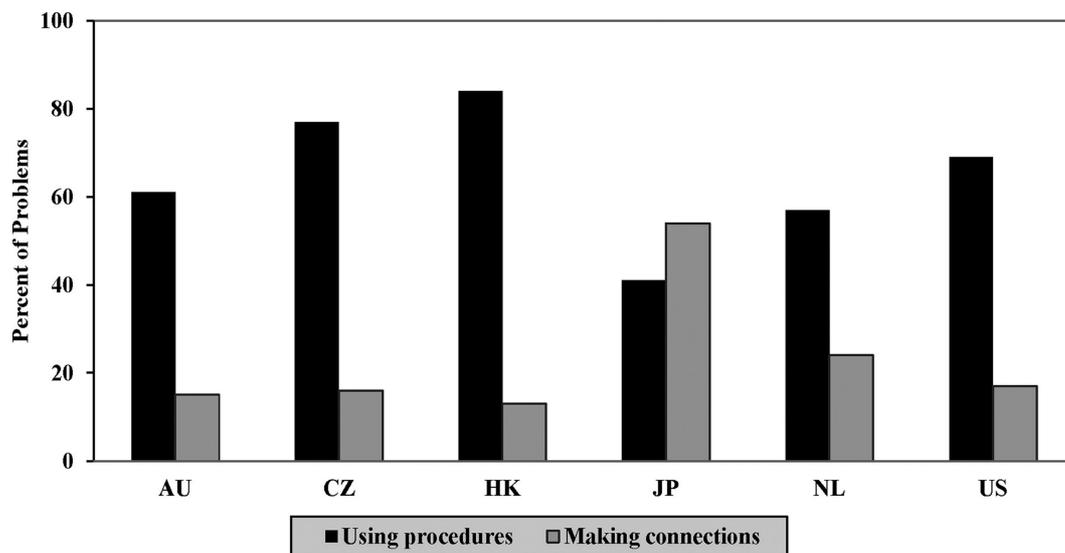


FIGURE 2 Percentage of problems that were coded Using Procedures and Making Connections. From "Improving Mathematics Teaching," by J. W. Stigler and J. Hiebert, 2004, *Educational Leadership*, 61. Copyright 2004 by Association for Supervision and Curriculum Development. Reprinted with permission.

of problems of each type. All countries have some Making Connections problems, though only Japan has more Making Connections problems than Using Procedures problems. Clearly, just presenting more Making Connections problems does not appear to be related to student achievement. Two of the highest achieving countries in the group are Hong Kong and Japan. Hong Kong has the lowest percentage of Making Connections problems, and Japan has the highest. The United States, it is interesting to note, falls in between Hong Kong and Japan. This pattern suggests that curriculum change alone (e.g., increasing the percentage of Making Connections problems in a textbook) will not necessarily result in improved learning.

A more compelling pattern emerges when we examine, in the videos, how the presented problems were actually worked on in the lesson. Although “struggle” per se was not coded, each problem was coded a second time to determine whether the teacher and students engaged with the problem in a way that required them to grapple with concepts or draw connections, or whether the teacher or students changed the activity to reduce the conceptual demand. As evidenced by the data, once a Making Connections problem was presented it was often changed, by the teacher into something else, most commonly a Using Procedures problem. In other words, just because a problem has the potential to engage students in productive struggle with mathematics concepts, it will not necessarily achieve that potential. For example, a teacher might give additional instruction or a worked example to aid the students in solving the Making Connections problem, which means that the activity becomes only practice for students.

In the United States, one of the reasons that problems do not succeed in engaging students in productive struggle is that

the students push back! Teaching is a complex system, and teaching routines are multiply determined. A teacher may ask students why, for example, the equation for finding the sum of the interior angles of a convex polygon works. But students may disengage at this point, knowing that the reasons why will not be on the final exam. Reasons why also may be misaligned with the students’ emerging sense of what mathematics is all about: a bunch of procedures to be remembered. Cultural and individual views of the nature of intelligence and learning, specifically as they relate to mathematics, and related processes such as stereotype threat and sense of belonging and self-efficacy, may undermine students’ motivation to engage in persistent effort toward achieving a mathematics learning goal (see, e.g., Blackwell, Trzesniewski, & Dweck, 2007; Dweck & Leggett, 1988; Heine et al., 2001; Walton & Cohen, 2007, 2011).

But teaching practice also may be limited by epistemological beliefs about mathematics. Although many K–12 teachers espouse of teaching for “conceptual understanding” (Bainbridge-Llath, 1976). Because the ability to successfully solve mathematics problems requires both conceptual skills, teachers regularly find these difficult to distinguish, and may define conceptual understanding and successful learning as comfort with procedures. For this reason, again we find it useful to articulate our hypothesis that students will be best served by learning to represent mathematics as a system of conceptual relationships in which problems and concepts must be connected.

Figure 3 presents just the Making Connections problems, showing the percentage of problems that were actually

change to:  
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stereotype threat,  
sense of  
belonging, and  
self-efficacy, may  
undermine....

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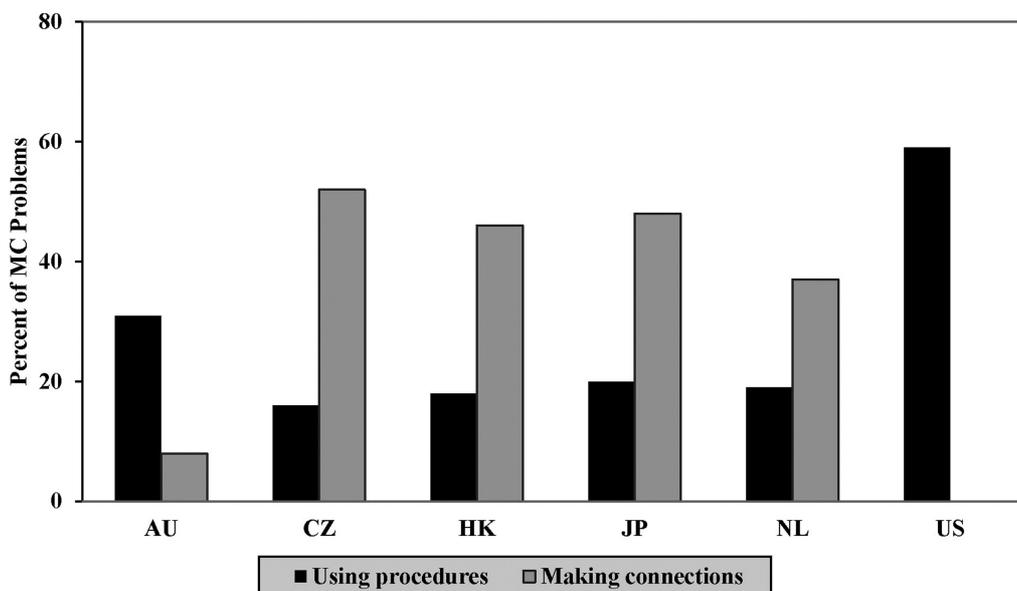


FIGURE 3 Percentage of making-connections problems that were implemented as using procedures and making connections. Note: Bars do not add up to 100% because there were other transformations that sometimes occurred. From “Improving Mathematics Teaching,” by J. W. Stigler and J. Hiebert, 2004, *Educational Leadership*, 61. Copyright 2004 by Association for Supervision and Curriculum Development. Reprinted with permission.

implemented as Making Connections problems versus those that were transformed into Using Procedures problems. Consider Hong Kong and Japan: Whereas they looked completely different when comparing the percentage of problems presented, they look very similar when we look just at how the Making Connections problems are implemented. Both Hong Kong and Japan, and most of the other countries too, are able to realize the full potential of Making Connections problems approximately half the time. The United States, now, is the outlier. Virtually all of the Making Connections problems presented in the United States were transformed into Using Procedures problems, or something requiring even less student conceptual participation. (The reason the percentages do not add up to 100 is that teachers sometimes did other things with Making Connections problems, e.g., just giving the students the answer without allowing them the opportunity to figure it out.)

The kinds of comparison processes that would be required for conceptual learning of mathematics would tend to happen during these Making Connections problems. But for a variety of reasons, such processes do not occur, at least with much frequency, in the U.S. classrooms.

Similar patterns were revealed in smaller scale, more detailed analyses of subsets of the TIMSS video data (Richland, Holyoak, & Stigler, 2004; Richland, Zur, & Holyoak, 2007). Richland et al. (2007) focused specifically on structured analogies, or opportunities for drawing connections and comparative reasoning. These investigators examined a subset of the United States, Hong Kong, and Japanese videotaped lessons to identify teacher practices in using and supporting students in making comparisons between problems, representations, or concepts. These included opportunities for comparisons between problems (e.g., “These are both division problems but notice this one has a remainder”) between mathematical concepts (e.g., between convex and concave polygons), between mathematics and nonmathematics contexts (e.g., “an equation is like a balancing scale”), or between multiple student solutions to a single problem.

Every instance identified as a comparison was coded to reveal teachers’ strategies for supporting students in drawing the connections intended by the teacher. An international team coded the videos, with native speakers from each country, yielding high reliability across all codes. Because (as previously discussed) the cognitive science literature on comparative reasoning indicates that novices in a domain often fail to notice or engage in transfer and comparative thinking without explicit cues or support, the codes were designed to determine the extent to which teachers were providing such aids. The codes were developed based on the cognitive science literature and on teacher practices observed in other TIMSS videotaped lessons, in an iterative fashion.

Specifically, the codes measured teacher instructional practices that could be expected to encourage learners to draw on prior causal knowledge structures and reduce working memory processing load. The codes assessed the pres-

ence or absence of the following teacher practices during comparisons: (a) using source analogs likely to have a familiar causal structure to learners (vs. comparing two new types of problems or concepts), (b) producing a visual representation of a source analog versus only a verbal one (e.g., writing a solution strategy on the board), (c) making a visual representation of the source analog visible during comparison with the target (e.g., leaving the solution to one problem on the board while teaching the second, related problem), (d) spatially aligning written representations of the source and target analogs to highlight structural commonalities (e.g., using spatial organization of two problem solutions on the board to identify related and unrelated problem elements), (e) using gestures that moved comparatively between the source and target analogs, and (f) constructing visual imagery (e.g. drawing while saying “consider a balancing scale”).

Teachers in all countries invoked a statistically similar number of relational comparisons (means of 14–20 per lesson). (These are different from the numbers of Making Connections problems identified in the analysis described previously, as these included also additional types of opportunities for drawing relationships.) Of interest, the data revealed that the U.S. teachers were least likely to support their students in reasoning comparatively during these learning opportunities. These findings were highly similar qualitatively to those from the overall TIMSS results, suggesting that U.S. teachers are not currently capitalizing on learning opportunities (i.e., opportunities for comparison) that they regularly evoke within classroom lessons. Both teachers in Hong Kong and Japan used all of the coded support strategies more often than did the U.S. teachers. As shown in Figure 4, some strategies were used frequently, others less often, but the Asian teachers were always more likely to include one or more support strategies with their comparisons than were teachers in the United States.

Overall, these data suggest that although the U.S. teachers are introducing opportunities for their students to draw connections and reason analogically, there is a high likelihood that the students are not taking advantage of these opportunities and are failing to notice or draw the relevant structural connections. At this point, we have come full circle in our discussion and return back to the students with whom we started. Community college developmental mathematics students don’t see mathematics as something they can reason their way through. For this reason, and no doubt other reasons as well, they do not expend effort trying to connect the procedures they are taught with the fundamental concepts that could help them understand mathematics as a coherent, meaningful system. The roots of their approach to mathematics can be seen in K–12 classrooms, where, it appears, teachers and students conspire together to create a mathematics practice that focuses mostly on memorizing facts and step-by-step procedures. We know from research in the learning sciences what it takes to create conceptual coherence and flexible knowledge representations that support transfer. But

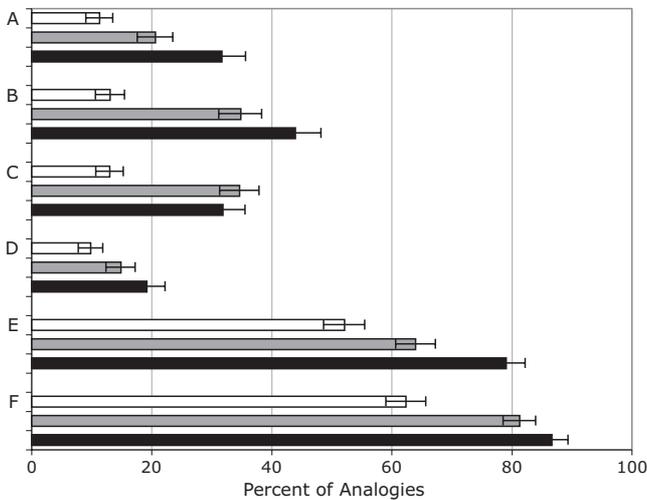


FIGURE 4 Percentage of analogies by region containing cognitive supports: (A) visual and mental imagery, (B) comparative gesture, (C) visual alignment, (D) use of a familiar source, (E) source visible concurrently with target, (F) source presented visually. Note. White denotes U.S. teachers, gray denotes Chinese teachers, and black denotes Japanese teachers. From "Cognitive Supports for Analogy in the Mathematics Classroom," by L. E. Richland, O. Zur, and K. J. Holyoak, 2007, *Science*, 316. Copyright 2007 by the American Association for the Advancement of Science. Reprinted with permission.

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we have found it difficult to implement such ideas in classrooms. Where do we go from here?

**HOW MIGHT TEACHERS BETTER SUPPORT STUDENTS IN SYSTEMATIC MATHEMATICAL THINKING? A RESEARCH AGENDA**

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The well-established cognitive literature on learning by structured comparisons, together with our analysis of current teacher practice and student outcomes in mathematics instruction, provides insight into strategies that might better leverage students' reasoning capacities to lead to meaningful understanding of mathematics. We propose several directions for research that would develop a foundation for integrating these ideas into classroom teaching. The first are experimental studies directly investigating the relationship between the pedagogical practices of comparison and analogy and student learning for flexible, transferable mathematics. Second, we outline the importance of understanding teacher and student epistemologies of mathematics in general, and epistemologies of comparison and cognition more specifically. This is essential to understanding the origin of the current problem and to develop recommendations that are likely to have an impact on practice. Third, we call for research on professional development strategies because the problem of how to impact teacher routines, particularly in this area of supporting students' connected, transferable thinking, have proven difficult.

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**Classroom Efficacy Tests of Strategies for Supporting Comparisons**

Although the TIMSS 1999 video data results just reviewed are provocative, they do not allow us to make causal inferences about the relationship between teacher practices and student learning. Several projects have begun to experimentally test the strategies for supporting comparisons that were identified as more frequent in the high-achieving countries (e.g., Richland & McDonough, 2010). So far, this work has found that using a combination of the most common support cues invoked by teachers in Japan and Hong Kong was not necessary to teach basic memorization and use of an instructed strategy, but these cues did increase students' flexibility and ability to identify relevant similarities and differences between instructed problems and transfer problems.

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We and other research groups are addressing the question of how to best design and support instructional comparisons. Our team is using controlled videotaped presentation of varied instruction, whereas other research groups are designing tools that aid teachers in leading instruction by comparisons as well as studying comparisons made by peers (see Rittle-Johnson & Star, 2007, 2009; Star & Rittle-Johnson, 2009). More work is needed to investigate strategies for optimizing teachers' current use of problems and comparisons that could be used to encourage students to draw connections and reason meaningfully about mathematics.

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Specifically, one of the strategies that needs further research is to better understand how students' prior knowledge structures are related to the types of representations and comparisons that are of most use in supporting sense making and relational reasoning. Adequate prior knowledge is essential for reasoning by comparison, primarily because without awareness of the fundamental elements of a representation, one cannot hope to discern the important structural correspondences and draw inferences on that basis (e.g., Gentner & Rattermann, 1991; Goswami, 2002). Yet surprisingly, using very familiar source analogs was the comparison support strategy identified in the TIMSS video studies that was employed proportionally least frequently by teachers in all countries. As reviewed earlier, the lack of well-structured knowledge about the source will limit students' schema formation and generalization from the target, as they are simultaneously acquiring and reasoning about the causal structure of both the source and target analogs. At minimum, the practice of using unfamiliar source analogs will impose high cognitive demands on the learner, making the additional supports for cognitive load yet more important to ensure that students have sufficient resources to grapple with the relationships between the two problems.

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Despite the challenges of drawing inferences from a relatively unfamiliar source analog, the literature is not clear as to whether generalization from two less well-known analogs can be as effective as between a known and less well-known analog, as

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word choice that leads to misreading; change to "even" or delete.

for causal thinking and sense making. Providing multiple representations certainly can be helpful, even when the domain is fairly novel, through a kind of analogical scaffolding (Gick & Holyoak, 1983).

980 However, this may vary depending on the background  
knowledge of the learner. Rittle-Johnson, Star, and Durkin  
(2009) found that general algebraic knowledge about manip- 1035  
ulating equations predicted whether students benefited at all  
from being taught through comparison between two solution  
985 strategies. Those who began instruction with better initial  
algebra intuitions about procedures for balancing equations  
(even if the procedures were not executed properly) benef-  
ited from this type of comparison, whereas those who were  
less prepared benefited more from serial instruction about  
990 two problems without explicit support for comparison, or  
from comparisons between two problem types. These stu-  
dents were working in collaborative pairs of peers, so those  
who began the lesson without adequate knowledge may not  
have had the level of support necessary to surmount the dif-  
995 ficulty of aligning and mapping the representations, but it is  
not clear what types of supports would have been sufficient.

Kalyuga (2007) proposed an “expertise reversal effect”  
for the role of cognitive load. This could be interpreted to  
imply that until students have adequate knowledge, they will  
benefit from all possible efforts to reduce cognitive load, in-  
1000 cluding reducing the instructional objective to have students  
encode the structure of a new representation. Once students  
have more expertise, however, they will gradually be able to  
handle more cognitive load and may actually benefit from  
1005 more effortful work to align and map between source and  
target analogs. Thus, the optimal level and role of teacher  
supports for relational thinking and sense making may shift  
over the course of students’ learning (cf. Koedinger &  
Roll, 2012).

1010 Overall, research is necessary to better understand the  
role of individual differences in prior knowledge and opti-  
mal relational learning conditions. Relational thinking and  
alignment between prior conceptual knowledge and new  
representations may be a way to characterize an impor-  
1015 tant element of the more general construct “struggle” as  
described by Hiebert and Grouws (2007). According to  
this construct, the level of struggle must be attenuated  
based on students’ level of prior knowledge so that the re-  
quirement to reason causes struggle, yet the challenge is  
1020 surmountable.

Although theoretically a very powerful framework for  
understanding the relationship between student learning  
needs and instructional content, one can imagine that  
this level of flexible instruction may be very challenging  
1025 for teachers. In particular, learning to use such strategies  
is difficult for novice teachers (Stein, Engle, Smith, &  
Hughes, 2008), and much more research is needed to  
better understand teachers’ beliefs about comparisons and  
students’ analogical reasoning.

## Teacher Knowledge and Professional Development 1030

The instructional strategies we have discussed to this point  
will be heavily reliant on a teacher who orients to mathemat-  
ics as a meaningful system and is able to flexibly vary his or  
her instruction based on diagnosis of students’ current knowl- 1035  
edge states. There are several parts to this description of a hy-  
pothesized ideal teacher that may be important to understand  
before we can know how to realistically integrate cognitive  
principles of comparison into classroom instruction.

The first pertains to the structured organization of teacher 1040  
knowledge and beliefs about the role of connections in math-  
ematics learning. In the community college sample, there  
was a clear distinction between the professors’ and students’  
*orientations* to mathematics, with the professors viewing  
mathematics as more of a meaningful system than their stu- 1045  
dents. K–12 mathematics teachers may be more similar to  
their students in their stored knowledge systems of mathe-  
matics, however, appearing more focused on rules (Battista,  
1984; Schoenfeld, 1988). Several measures have been de- 1050  
signed to assess teacher knowledge about mathematics con-  
tent and about students’ mathematical thinking (e.g., Hill,  
Ball, & Shilling, 2008; Hill, Schilling, & Ball, 2004; Kerst-  
ing, Givvin, Sotelo, & Stigler, 2010), yet we need to learn  
more about teachers’ beliefs and knowledge about mathemat-  
ics as a system, specifically with respect to the roles of multi- 1055  
ple representations and drawing connections among content.  
In particular, it will be important to try to discover where  
students acquire their belief that mathematics is a series of  
memorized rules.

International studies suggest that despite variability in 1060  
teacher expertise in the domain within the United States,  
there may still be differences in the ways that the mathe-  
matical knowledge of American teachers is organized when  
compared with either mathematics domain experts or with  
teachers in other countries, particularly with respect to the role 1065  
of interconnections within the content. Ma (1999) found that  
the U.S. mathematics teachers had taken more mathemat-  
ics courses than the average Chinese mathematics teachers  
in her sample, but the Chinese teachers’ representations of  
mathematics were far more systematic, interconnected, and 1070  
structurally organized. The U.S. teachers tended to represent  
the mathematics curriculum as linearly organized, whereas  
the Chinese teachers’ representations of the curriculum more  
closely resembled a web of connections. Further research in-  
ternationally as well as within the United States may better 1075  
reveal teachers’ underlying conceptualizations of mathemat-  
ics, with particular attention to the role of interconnections  
and meaningful systems of relationships, in much the same  
way we have gathered information from the community col-  
lege students (Givvin et al., 2011). Greater understanding 1080  
of teachers’ knowledge of mathematics may aid in develop-  
ing procedures or tools to better facilitate teacher practices

and to optimize the effectiveness of comparison strategies as pedagogical tools.

1085 Finally, we join the NCTM and other mathematics teacher educators in calling for further research on professional development strategies for promoting a conceptual shift for teachers from teaching mathematics as memorization of procedures to a structured system of goal-oriented problem solving. We in particular emphasize the need for professional development to support teachers in learning how to represent problems as goal-oriented systems that can be connected meaningfully to other problems, representations, and concepts. As we have identified in the TIMSS analyses, U.S. teachers are not currently leveraging opportunities for drawing connections and thereby encouraging students to organize their knowledge around mathematical relationships. We require research to better understand how to provide such knowledge to teachers in a way that is usable. In addition, it may prove useful to support teachers through better textbooks and resource tools that include more connected, comparison-based suggested instruction.

In sum, we posit that leveraging students' reasoning skills during K–12 mathematics instruction may be a crucial way to enhance their ability to develop usable, flexible mathematics knowledge that can transfer to out-of-school environments. U.S. teachers are not currently providing most students with opportunities to develop meaningful knowledge structures for mathematics, as revealed by studies of community college students' mathematical skills and video-based observations of teacher practices. Cognitive scientific research on children's causal and relational thinking skills provides insights into strategies for supporting students in gaining more sensible, meaning-driven representations of mathematics. However, more research is necessary to determine how these ideas may become effectively integrated into classroom teaching.

### ACKNOWLEDGMENTS

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# Resisting Overzealous Transfer: Coordinating Previously Successful Routines With Needs for New Learning

Daniel L. Schwartz, Catherine C. Chase, and John D. Bransford

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Daniel L. Schwartz, Catherine C. Chase, and John D. Bransford

## Resisting Overzealous Transfer: Coordinating Previously Successful Routines With Needs for New Learning

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Many approaches to instruction focus on helping people learn to recognize “the old in the new”—to turn what would otherwise be novel problems into familiar patterns that can be solved efficiently through the reuse of prior learning. Instruction that leads to efficient transfer is important, but it can also promote what we call “overzealous” transfer (OZT), where people focus primarily on seeing the old in the new because old routines have been successful before. As a result, OZT can hinder opportunities for new learning, and this can further diminish adaptive transfer later on. We relate OZT to “negative transfer,” provide experimental examples of OZT, discuss how a number of professions have developed procedures for avoiding OZT, argue that many common approaches to instruction and assessment may inadvertently produce OZT, and suggest some implications for future research.

Heraclitus, a famous pre-Socratic philosopher, stated that no two experiences are identical; people never step into the same river twice. Nevertheless, people do find consistency in variation and see the same river, even if it contains different water from moment to moment. If people experienced every situation as completely novel, the demands of constant adaptation would make life intolerable. But if people treated every experience as the same, life would be impossible. Transfer research can ask how people strike the balance between reusing previous learning to treat new situations like old ones, while also avoiding the tendency to overgeneralize prior learning and miss what is new.

Hatano and Inagaki (1986) noted that some people (routine experts) restrict themselves to familiar settings and challenges that limit their need to see novelty. Others (adaptive

experts) are more likely to move outside of existing comfort zones to take on new challenges that require transfer plus some adaptation to meet contextual variation. We frame our discussion with the goals of helping people to be more adaptive, even if they never have the opportunity to become adaptive experts.

### FAILED TRANSFER AND POSITIVE TRANSFER

#### Failed Transfer

The phenomenon of transfer has been explored from many perspectives, for example, how identities cross participation boundaries (Beach, 1999) or how foundational capacities such as executive function can support many tasks (Blair & Razza, 2007). Educators have been especially concerned with people’s frequent failures to transfer learning from problem

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to problem and from setting to setting (see Bransford et al., 2006; National Research Council [NRC], 2000). Whitehead (1929) coined the term “inert knowledge” to describe cases where people have learned relevant knowledge and skills yet fail to spontaneously access this knowledge despite its relevance for problem solving. Examples include failures to transfer skills and knowledge learned in school to real life settings (Lave, 1988), failures to utilize cues for problem solving unless explicitly instructed to do so (e.g., Lockhart, Lamon, & Gick, 1988; Perfetto, Bransford, & Franks, 1983), failures to use recently learned problem solutions to solve an analogous problem where the cover story has changed (Gick & Holyoak, 1983), and failures to use expertise in one area to solve problems in another (Chase, in press).

### Positive Transfer

To overcome transfer failures, a major strategy is to help people learn to “see the old in the new.” Chi and VanLehn (2012/this issue) summarize the cognitive literature:

Thus, we can safely say that all theoretical perspectives would agree that transfer means there ought to be some “saving” (sometimes measured in terms of speed, efficiency, or errors) from one context towards performing in a new context without substantial relearning. (p. XX)

From this perspective, schools emphasize transfer because it is resource effective—it is easier to reuse than create afresh.

Researchers have studied a variety of instructional strategies for decreasing failed transfer and increasing positive transfer. Wertheimer (1959) provided a classic example of helping students think about and represent geometric area that subsequently supported transfer, from learning about a simple figure to a new figure with more complexity. Without his new approach to instruction, students looked at the new transfer problem and tended to say they had never seen it before (e.g., see NRC, 2000).

Gick and Holyoak’s (1983) classic studies also show how a problem solution can fail to support transfer to a similar problem if the later problem has a different cover story and occurs a mere two pages later. However, if people first have a chance to make the connection between two analogous problems, then they make the transfer to the next problem much better (see also Brown & Kane, 1988). Transfer is often aided by seeing the same idea in at least two different contexts (NRC, 2000). In other cases, transfer improves if ideas are initially presented in ways that are problematized rather than simply presented as declarative statements (e.g., Adams et al., 1988; Martin et al., 2007; Needham & Begg, 1991). Instruction that helps students differentiate the applicability conditions of problem solutions also improves transfer because people can better recognize contextual cues for the use of their knowledge (Bransford, Franks, Vye, & Sherwood, 1989).

Researchers have also shown that many traditional transfer measures are not sensitive enough to reveal important learn-

ing experiences that support transfer from one situation to another. Most assessments used in transfer research are “one shot” rather than iterative (people answer one problem and move to another unrelated problem) and “sequestered” in the sense that people have no access to resources for new learning. As argued elsewhere (Bransford & Schwartz, 1999), sequestered problem solving often represents too blunt an instrument for discovering whether and why previous experiences have prepared people to transfer for future learning, for example, by preparing them to understand a lecture, notice new things, ask more relevant questions, seek feedback, and do other things as they engage in (what need to be) information-rich transfer tasks.

Overall, it seems fair to claim that knowledge of how to improve positive transfer and how to measure it with more sensitivity has improved considerably over the years. Still, all is not well with respect to understanding positive transfer. Many examples of negative transfer still abound, and many routines for learning represent instances of negative transfer.

## NEGATIVE TRANSFER AND OVERZEALOUS TRANSFER

### Negative Transfer

Negative transfer refers to the overgeneralization of prior learning. With negative transfer, people do not fail to transfer; instead, they transfer learning to a situation where it is inappropriate to do so (e.g., Ross, 1987). From early on, the transfer literature recognized problems of negative transfer, where previous learning hurts new learning and problem solving. In many instances, negative transfer appears as interference that people recognize but cannot overcome at first. For instance, verbal learning research asked participants to associate stimuli in Set A with responses defined by Set B (e.g., tree → ball; car → house). This association subsequently interfered with the participants’ abilities to learn the association of the stimuli in Set A with a new set of responses defined by Set C (e.g., now learn tree → chair, instead of tree → ball). Similarly, switching from a car with a clutch and stick shift to one with an automatic transmission often results in people trying to press the clutch of the new car and finding it is not there. Over time, people extinguish the unnecessary negative transfer of the “clutch” response. But they can also experience positive transfer of aspects of driving, like keeping an eye on the road and mirrors and using the brakes and steering wheel appropriately. So transfer can have both negative (attempts to find the clutch) and positive (knowing how to drive in general) impacts on people’s subsequent behaviors, rather than simply a single good or bad effect.

Other instances of disappointing transfer appear to be the result of people assuming that a new situation is like an old one. They do not recognize that a new situation is something different from those before, and they are unaware of the negative transfer. For example, McNeil (2008) provided children

spelling - change to "buses"

with a novel problem that depended on arithmetic:  $7 + 2 + 5 = 7 + \dots$ . The children transferred their addition skills to the novel problem format by adding up all the digits on both sides of the equation to find a total (i.e., 21). They did not appear to appreciate the novel equivalence format of the problem.

Similarly, Silver (1986) provided students with a word problem on how many busses are needed to transport a group of students. He found that many students concluded that the answer was  $3\frac{1}{3}$  buses, because they approached the "how many buses do we need" problem by simply dividing the seating capacity of each bus with the number of people going on a trip—evidently forgetting that  $\frac{1}{3}$  buses are in short supply. Reusser (as cited in Schoenfeld, 1989) presented middle school students with the following problem in the context of other mathematics problems: *There are 26 sheep and 10 goats on a ship. How old is the captain?* Approximately three fourths of the students came up with a numerical answer. As noted elsewhere (Bransford & Stein, 1993), one of us (JB) gave this problem to our child in fifth grade with a strong belief that there would be laughter followed by a statement like "That's ridiculous." Instead, our child looked at the problem, smiled confidently, and gave the answer 36. When asked why that was the answer, he responded (we paraphrase), "Because that's the kind of thing you do in problems like this. This was an easy one, I only had to add."

### Overzealous Transfer

In the examples of negative transfer, it seems safe to say that students gave wrong answers—but wrong answers from whose perspective? In many cases, it is not so clear that a transfer is negative (Lobato, 2003, 2012/this issue). From the vantage point of the students, they may believe they are doing the right thing, and without appropriate feedback they cannot know otherwise. Of particular concern are situations where students transfer skills, knowledge, and routines that are effective for the task at hand but may nevertheless be suboptimal in the long run because they block additional learning. We will call this *overzealous transfer* (OZT)—people transfer solutions that appear to be positive because they are working well enough, but they are nevertheless negative with respect to learning what is new.

Luchins and Luchins's (1959) classic water jug studies of Einstellung (mental set) illustrate problems with OZT. They gave participants three different sizes of jars and asked them to use these to reach a particular target amount of water. To illustrate, imagine a target goal of 25 oz of water and receiving three jars of water that contained 29, 3, and 5 oz of water, respectively. One solution is to find a way to subtract 9 oz from 29. One could pour water from the 29-oz jar into the 3-oz jar three times (emptying it each time). This would yield 20 oz in the big jar. Then one could pour the 5-oz jar into the big jar to reach 25 oz.

Participants in the Luchins's experiment encountered many variations of the water jar problem. A major feature

of the experiment was to present people with blocks of problems (known only to the experimenters) that each required a similar set of procedures (e.g., subtracting water from a larger jar, then adding water from a smaller jar). People got better within a block of problems because they developed a helpful mental set for solving a series of related problems. However, the set also caused OZT. Special test problems were inserted throughout the study, which could be solved much more simply than by using the routines the participants had learned. Most participants did not notice the simpler solution and relied on their mental sets. It is noteworthy that the use of the overly complex procedures did not cause errors—people were still able to reach the target numbers. They were just less efficient because they did not let go of their complex mental set to seek a simpler solution.

The Luchins and Luchins (1959) study illustrates three important points about OZT. First, OZT is a type of negative transfer in that people apply old learning in situations where it would be more effective to avoid whole-cloth transfer. Instead, people should selectively transfer some aspects of their knowledge but not others. For example, it was useful for participants to transfer their general understanding of the water jug task across problems, but it was suboptimal to transfer the specific solutions. The second point is that OZT transfer is frequently "good enough" to meet the apparent demands of the task. When there is no mechanism for negative feedback, the transfer of previously successful routines will seem like a positive transfer rather than a negative one. The third point is that OZT can cause people to miss opportunities for new learning. Reliance on old routines that seem to work (at least partially) reduces the need for seeing and adapting to what is new. As we describe next, many instructional routines exacerbate OZT, because they provide positive feedback for getting the right answer, without providing negative feedback that the students missed what is new to be learned. In this case, students are not simply "satisficing" (Simon, 1956), but instead they believe they are doing what they are supposed to be doing. In this sense, transfer is overzealous<sup>1</sup> because people are eagerly applying prior routines that they believe will successfully solve the problem at hand.

delete comma

### INSTRUCTION AND OVERZEALOUS TRANSFER

OZT is not confined to the transfer of concepts or procedures covered in a lesson. OZT can also occur with instructional and learning routines. For instance, in a study of beginning teachers, Grossman (1989) described how one teacher taught *Hamlet* by transferring his own school experience. He loved Shakespeare and learned it in college through a "close reading" of the text, so he taught his students in the same

<sup>1</sup>We do not mean to use the term *overzealous* to connote an affective component of transfer. For instance, we are not claiming that students are transferring with a strong sense of passion.

260 way. This appears to be a case of OZT, and by Grossman's  
analysis, the high school students learned poorly. In contrast,  
a second teacher tried to adapt to the needs of his students. He  
began by first asking them to think about the circumstances  
265 that might drive them so mad that they would contemplate  
murdering another human being. Only after students had se-  
riously contemplated the major issues of the play did they  
begin reading. Rather than transfer in his college experience  
whole cloth, this teacher attempted to learn what might make  
an antique story compelling to modern-day students.

270 OZT can occur in the context of learning, problem solv-  
ing, and even teaching. A common instructional and learning  
routine is the "tell and practice" (T&P) method. T&P was  
derived from work on problem solving, which notes that it is not  
enough to simply provide general statements about problem-  
solving strategies (Simon, 1980). People must also practice  
275 solving problems so they can learn to relate general solutions  
to specific applications. So teachers and texts typically pro-  
vide students with sets of "application problems" to solve as  
homework or after reading a textbook chapter. T&P is an im-  
provement over just telling. But, in practice, there are often  
280 shortcomings in implementing this approach.

Richland, Stigler, and Holyoak (2012/*this issue*) argue  
that an overuse of T&P in U.S. schools helps explain why  
they do relatively poorly on international comparisons of  
math. In reviewing the work of Heibert and Stigler (2004),  
285 as well as that of Richland, Zur, and Holyoak (2007), they  
note that American classrooms and their international peers  
do not differ greatly in the amount of curricular material  
designed for active inquiry. The difference is that American  
instructors rely on a set of T&P routines to teach the material,  
290 so there is effectively no inquiry. The teachers overgeneralize  
an instructional routine.

T&P is what Tyack and Cuban (1995) called a com-  
mon "grammar of schooling." It is also a common grammar  
of transfer research. Schwartz, Chase, Oppezzo, and Chin  
295 (2011) documented that 75% of studies on the transfer of  
science, technology, engineering and mathematics (STEM)  
content used some form of T&P for both control and treat-  
ment conditions, which further indicates the prevalence of  
T&P routines. Our major concern is that the routines that  
300 people transfer can have a tremendous influence over what  
they will learn and may undermine other manipulations de-  
signed to improve the transfer of concepts and skills.

One possible problem with T&P routines is that they can  
overemphasize efficiency at the expense of discovering new  
305 ways of seeing and doing (Bonawitz et al., 2011). The reason  
is that T&P is a familiar learning routine that focuses on  
executing what one has been told. Although valuable for  
exercising an idea or procedure, it can come at the expense  
of engaging in new learning, such as noticing the unique  
310 contextual structures that call for the application of an idea  
or procedure.

A recent study demonstrates how T&P routines can in-  
advertently interfere with appreciating key contextual struc-

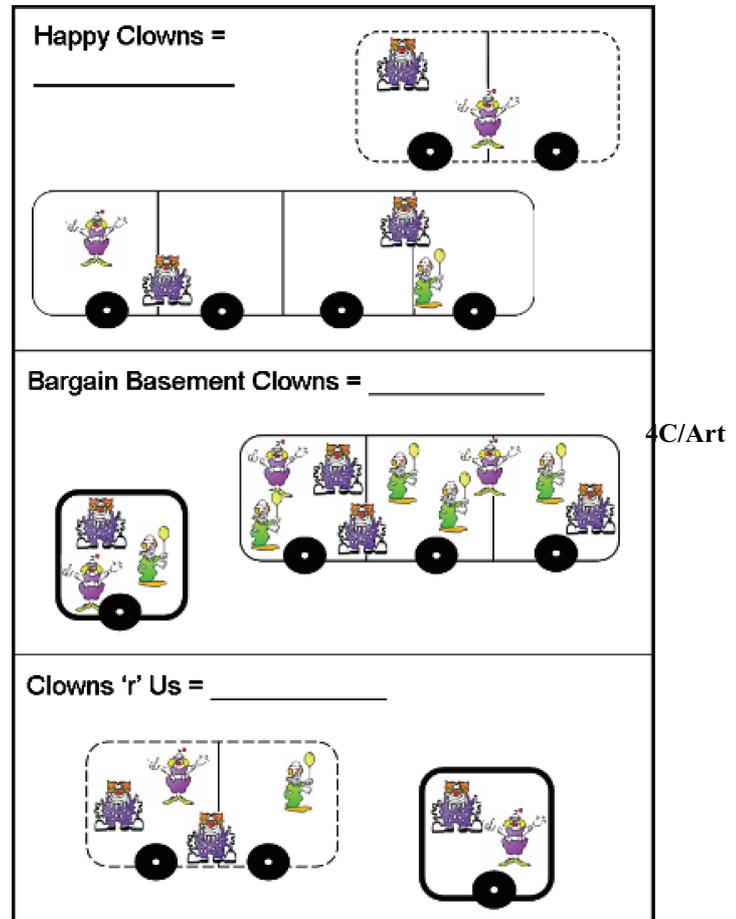


FIGURE 1 Worksheet for learning about density. *Note.* Each row of the worksheet represents a company who uses the same average density of clowns per bus compartment. Students in a "tell and practice" condition were told how to compute density and practiced by finding the density used by each company. Would the students learn that density comprises a ratio of mass (clowns) to volume (bus compartments)? From "Practicing Versus Inventing With Contrasting Cases: The Effects of Telling First on Learning and Transfer," by D. L. Schwartz, C. C. Chase, M. A. Oppezzo, & D. B. Chin, 2011, *Journal of Educational Psychology*, 103. Copyright 2011 (color figure available online).

315 tures (Exp. 2; Schwartz et al., 2011). Eighth-grade students  
in a T&P treatment were told about some everyday exam-  
ples of density and the formula that describes them ( $d = m/v$ ).  
They also received a worked example for how to use  
the formula to find answers. They then practiced with the  
application worksheet shown in Figure 1. Their task was to  
320 find the density each company uses to ship its clowns to  
parties. Each company, designated as a row in the worksheet,  
ships clowns using a constant density of clowns to buses. The  
worksheet comprises a set of contrasting cases designed to  
help students notice the ratio structure of density: A company  
325 uses the same ratio so that both instances are proportional.  
At the same time, different companies use different ratios,  
so students can see differences defined by ratios rather than  
simple counts of clowns or buses.

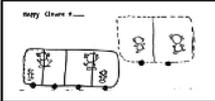
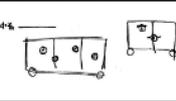
	High Structure	Low Structure
High Surface		
Low Surface		

FIGURE 2 Evidence on learning the ratio structure of density. Note. Examples of free-recall drawings separated by whether they included the proportionate density structure and whether they included surface features about clowns. Adapted from “Practicing Versus Inventing With Contrasting Cases: The Effects of Telling First on Learning and Transfer,” by D. L. Schwartz, C. C. Chase, M. A. Oppezzo, & D. B. Chin, 2011, *Journal of Educational Psychology*, 103. Copyright 2011.

Students finished the worksheet in approximately 10 min and were more than 90% accurate at determining the densities. So they were successfully applying the T&P routine. However, the key research question was whether students would also pick up the ratio structure of density. To find out, students were asked to redraw the worksheet a day later from memory.

Figure 2 provides examples of drawings. To receive credit for re-creating the deep ratio structure, students did not have to remember the exact ratios; they just had to produce a pair of proportionate ratios for a given company. Despite being 90% accurate in applying the density formula, they were only 38% accurate in detailing that a given density is comprised of equivalent ratios. (Figure 2 also shows that some students included surface details, such as dotted lines, which was uncorrelated with recreating the deep structure.)

In their zeal to apply the formula, the students turned the physics formula into a division problem. They mapped the variables of the formula (mass and volume) to the features of the cases (clowns and bus cubes), so they could execute the relevant division (mass by volume). They saw the old in the new, namely, a math problem. They did not see the ratio structure of density, which was the important new content. The students were unaware that there was something new to be learned, in part, because they could solve the problems using familiar T&P learning routines. Even when a topic is marked as novel, students can overzealously transfer learning routines that are intended for solidifying skills rather than inducing new patterns. As we describe next, this can have strong consequences for subsequent transfer.

#### INSTRUCTIONAL TECHNIQUES FOR BLOCKING OZT

The previous section described the OZT of a common learning routine called T&P. This section shows its consequences

for transfer of concepts. Transferring a suboptimal learning routine *in* to a situation can make transferring the content *out* of the lesson less likely. In this way, the OZT of a learning routine can set the stage for a cycle of transfer failures. In this section, we also describe an instructional technique designed to help students discover what is novel about a problem situation, and we show how it affects transfer.

In the previous study, there was a second treatment designed to skirt the OZT of T&P. It used an instructional technique called Inventing with Contrasting Cases (ICC). Students in the ICC condition received exactly the same worksheet (Figure 1), but they were not told about density or its formula beforehand. Instead, they had to invent their own ways to find the “crowdedness” used by each company. They had to invent an index of crowdedness that could be applied to all the companies. The ICC students took about the same amount of time as the T&P students. Despite having little guidance and no feedback, ICC students were quite successful at this task though slightly less accurate than T&P students. About 85% of their crowdedness indices corresponded to the correct density value. Even so, on the next day, 58% of their worksheet redrawings included the proportionate ratio structure of the companies, compared to the 38% in the T&P condition.

These differences had implications for transfer. Over the next few days, the T&P students received a general lecture on the importance of ratio in physics, as in the cases of density, speed, and several other science topics. They then completed three more activities following the same T&P format as the initial lesson; one on density and two on speed (also an extensive ratio,  $S = d/t$ ). Each time the topic of the worksheet was different so students could experience ratio across multiple contents.

The ICC students also received the three worksheets and had to invent an index for each one, as before. It was not until after these inventing activities that they finally heard the lecture that explained ratio and the canonical formulas. Both groups then solved a series of standard word problems on density and speed for about 15 min.

A week after completing the lessons, the students in both conditions received a pair of posttests. One posttest asked them to solve computational and qualitative word problems about density and speed. The two conditions achieved the same level of accuracy (~65%), which indicates that ICC did not come at the expense of learning the standard solutions relative to the T&P treatment. The second posttest held the transfer problem. Figure 3 shows that students had to describe the stiffness of different trampoline fabrics (i.e., the spring constant). The question was whether students would use a ratio to describe the stiffness of the fabric—number of people by the stretch of the fabric (number of rungs).

By this time, participants in the T&P condition had received a series of analogies that all involved the structure of ratio, they were told the general principal that connected the examples, and they successfully followed a set of worked

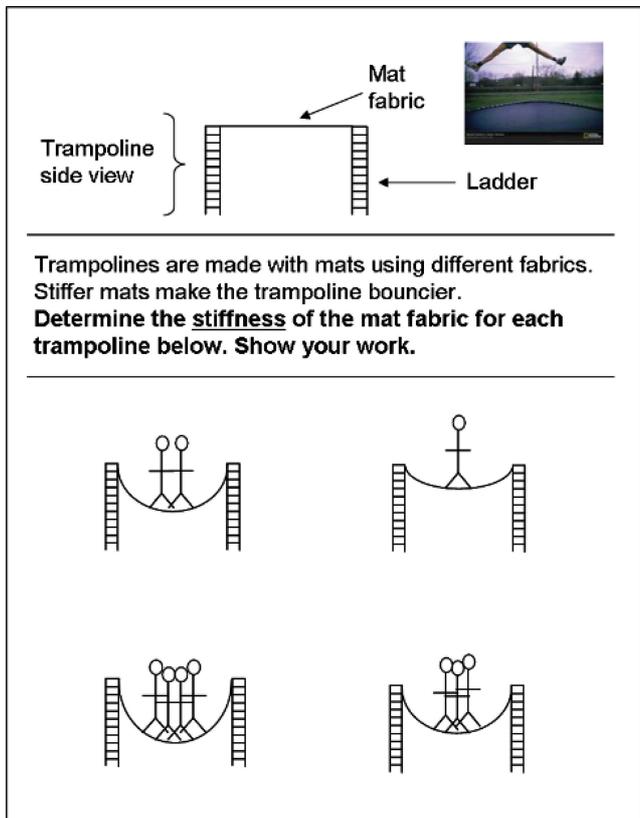


FIGURE 3 A problem used to test the transfer of the ratio concept. Note. The question was whether students would use a ratio of people by stretch distance to describe the fabrics for each trampoline. From "Practicing Versus Inventing With Contrasting Cases: The Effects of Telling First on Learning and Transfer," by D. L. Schwartz, C. C. Chase, M. A. Oppezzo, & D. B. Chin, 2011, *Journal of Educational Psychology*, 103. Copyright 2011 (color figure available online).

examples to prepare them for the worksheets on a variety of topics. All of these are known to support transfer (e.g., Brown & Kane, 1988; Gick & Holyoak, 1983; Pass & Van Merriënboer, 1994). Nevertheless, the zeal to follow the T&P learning routine trumped the effectiveness of these techniques, and this had consequences for the trampoline transfer problem. About 23% of the T&P answers used a ratio structure to describe the stiffness of the trampoline fabrics, with most of the answers simply counting the number of people or the number of rungs, but not both. In contrast, the ICC students correctly used a ratio 51% of the time. Of interest, the study also found that the low-achieving ICC students (based on class grades) outperformed the high-achieving T&P students at transfer (41% vs. 33%, respectively). We interpret the poor performance of the T&P group as a result of OZT. They practiced what they had been told when using the worksheets, which makes sense, given that it was good enough to achieve the right answers on the worksheets. However, this success had the hidden consequence that the students did not learn what was new, namely, the ratio structure of many physical phe-

nomena. As a result, they did not transfer because they had never learned to recognize the applicability conditions for the use of ratio.

Other experiments and transfer tasks replicated these findings and demonstrated strong benefits of ICC over T&P, even when the ICC students never heard a lecture on ratio before the transfer problem. It is important to note that the ICC students were not left to their own devices to come up with a new learning routine. The worksheets were carefully designed as contrasting cases that highlighted the ratio structures, and students were specifically told to invent a quantitative index to characterize the cases. Across all the inventing worksheets, ICC students got 85% of the answers correct (T&P students were at 92%). This differs from prior studies that have found an advantage for T&P instruction compared to unscaffolded exploration (Klahr & Nigam, 2004; Tuovinen & Sweller, 1999). Many students do not have good learning routines for exploration, given that American schools use a heavy diet of T&P. It makes sense that without routines for organizing their learning, students would flounder in free-exploration conditions compared to the strong guidance of T&P. The preceding ICC lessons were one way to provide students with a tractable learning routine to help them adapt to what was new (to them) about the physical phenomenon. It effectively stopped students from overzealously transferring in suboptimal learning routines while providing an alternative learning approach.<sup>2</sup>

Additional studies have also shown benefits of asking students to invent their own descriptions of a set of well-organized data compared to T&P. Schwartz and Bransford (1998) demonstrated the benefits of invention for transfer with college students learning principles of cognitive psychology. Schwartz and Martin (2004) made a similar demonstration with high school students learning statistics. Kapur (2008) found that withholding answers improves the depth of learning and transfer, even when students often fail to generate the correct solutions. Parker et al. (2011) redesigned an American Government, Advanced Placement (AP) course, so that it was organized around a set of challenges where students engaged in relevant activities (e.g., participating in a mock trial) prior to receiving detailed lectures and readings. It inverted the usual learning routine, so that "telling" came after, rather than before, substantive problem solving. Students who took this version of the AP course scored as well as, or better than, control groups that used a traditional AP course (highly memory oriented), and they did better on

<sup>2</sup>A reasonable question is whether it would work to have students complete T&P and then invent afterward. Although it remains to be tested, our speculation is that they would just apply the formulas they had been taught without finding the deep structure of the ratios. It would be difficult for students to forget what they had just learned to only come up with the exact same answer through inventing. If the problems were masked so that students did not know they were finding density or speed, then they would be inventing again rather than reusing what they already knew, and we would expect them to show the benefits of avoiding the zealous application of division.

485 a “complex scenario test” where students were asked to solve novel problems. Similar kinds of “inquiry first” instruction have yielded more effective and flexible transfer in middle school science (Shutt, Vye, & Bransford, 2011). Ideally, there would be more studies to report, but as mentioned earlier, most studies of transfer have used a “tell-first” approach for all the conditions.

490 Results like these led Schwartz, Bransford, and Sears (2005) to hypothesize that flexible transfer could be enhanced through the use of well-designed innovation activities that help students first recognize applicability conditions before learning the efficient solutions through T&P. The innovation activities, which can seem inefficient at first glance, speed up the subsequent acquisition of the efficient solution, once delivered, because students understand what the solutions need to accomplish. In addition, starting with an innovation activity blocks the natural tendency toward an OZT that stops students from noticing what is new. This does not mean that all lessons should begin with guided-discovery activities. For example, improving automaticity depends on practice that emphasizes speed and accuracy. Guided-discovery activities are most appropriate when the goal is to help students see what is new (for them).

#### PROFESSIONALS WITH METHODS FOR AVOIDING OZT

510 People need efficient schemas and routines that enable them to handle recurrent situations quickly and effectively. When it is possible to anticipate a stable future, routine expertise is appropriate. For instance, in the foreseeable future, English words will be read left-to-right, top-to-bottom; will be comprised of letters; and will have spaces in between. For decoding words, we want to put students on a trajectory of routine expertise, so they can take advantage of the stability of words with high efficiency. For other topics, there is less of a guarantee that the future will resemble the past. When learning in school, topics change from week to week, and many workplace demands change with the times. In these cases, we want to help people rely on their past efficiencies but also go beyond those efficiencies so they can better learn what is new. For schools, it seems possible to design instruction that avoids the perils of OZT and helps students balance important routines with the needs for new learning.

525 A different challenge involves preparing people to avoid OZT once instruction is no longer present. Are there ways to prepare people for the transfer of learning routines that, despite being routines, manage to block OZT?

530 Professionals provide a useful test case. They have accumulated a body of knowledge that enables them to complete their work effectively, so they do not need to incur the inefficiencies of learning from each new instance. This may lead them to OZT, because they might see each new instance as an old one. At the same time, they may have learned routines to

resist overassimilation, so they can seek what is novel rather than always use prepackaged solutions. 535

Miller (1978), who studied information designers, provided a useful example. He found that some designers were “virtuosos” who actively sought contextual information to adapt their designs to specific client needs. These designers fit the description of adaptive experts, who seek to understand the variability of new contexts (Hatano & Inagaki, 1986). However, he also found designers who were “artisans.” They used off-the-shelf solutions to satisfy their clients. These designers fit the description of routine experts, who rely on the efficiencies of prior knowledge to get the job done. We are especially interested in examples of adaptive experts. 540 545

One example comes from Wineburg’s (1991) comparison of college students and professional historians. Working individually, they each received a set of source documents and had to explain what happened at the Battle of Lexington. The historians were not experts in American history, but they were professional historians who had specific approaches to avoid OZT. They did not assume that the words in each document were true, but rather, they attempted to better understand the intents of the documents’ authors and the historical context in which they were written. In contrast, college students did not attempt to explore and understand the perspective behind each data source; they tried to understand the documents based on their own experiences. From the vantage of most schooling practices, the college students demonstrated appropriate transfer. They tried to make sense of the facts in the texts by connecting them to prior knowledge (e.g., Anderson & Pearson, 1984; Bransford & Johnson; 1972). In contrast, the experts had learned a set of approaches that enabled them to avoid the OZT of this familiar reading routine. 550 555 560 565

Using a similar research design, Atman, Chimka, Bur-sic, and Nachtmann (1999) studied engineering students and professional engineers. Participants were asked to design a playground, given a set of initial specifications. Compared to students, the professional engineers were much more likely to ask for additional information from stakeholders rather than assume they fully understood the design context, and seniors in engineering were more likely to ask relevant questions than were juniors, who in turn asked more than sophomores did. So, like the professional historians, professional engineers seek out new information so they can develop a better understanding and formulation of the problem context. 570 575

In addition to seeking new information rather than assuming they know enough to get the job done, Martin and Schwartz (2009) demonstrated that adaptive experts also work to organize that information, even when it is not strictly necessary to get the job done. They looked at graduate students—early-stage experts—in STEM domains. They compared them to undergraduates solving a set of novel diagnosis problems. On sheets of paper, the students received cases that described prior patients, their symptoms, and their diagnoses. Their task was to use these cases to help order tests and make diagnoses for new simulated patients on a 580 585

590 nearby computer. The undergraduates immediately turned  
to the computer. For each new patient that appeared on the  
screen, they would search through the sheets of paper to de-  
termine what test to order and, based on the test results, they  
would sift through the papers again to decide the next test  
595 and/or diagnoses. This was sufficient to get by, and the un-  
dergraduates' ultimate diagnoses were excellent. In contrast,  
by the time the undergraduate students were nearly done, the  
graduate students had not diagnosed a single patient!

600 Every single graduate student spent approximately the  
first 10 min creating a representation of the original cases,  
for example, by making a tree or matrix of the symptoms and  
diseases. When the graduate students finally turned to the  
computer to start diagnosing, they never looked back to the  
sheets. So, whereas the undergraduates handled each case as  
605 it arose, which was sufficient to complete the task at hand,  
the graduate students gave up short-term efficiency to create  
a general (visual) solution that could handle any case. The  
graduate students had the same diagnostic accuracy as the  
undergraduates, but they were better at ordering the minimal  
610 number of tests to make a diagnosis.

We surmise that the graduate students had learned the  
value of considering the long-term nature of tasks when it  
comes to handling data and that this prompted them to find a  
general solution that would ensure long-term success across  
615 many problems. We do not know if the graduate students  
were explicitly taught to create data visualizations, but we  
do know that instruction can be enhanced so that students  
transfer the idea of creating "smart tools" that can handle a  
range of contextual variation (Schwartz, 1993; Zech et al.,  
620 1998).

In each of the preceding examples, the experts had  
domain-specific routines for avoiding OZT. The graduate stu-  
dents had learned to look for general solutions when it comes  
to data analysis, the historians had learned to contextualize  
625 documents to their sources, and engineers had learned to  
ask for more information from clients in a design task. The  
routines were tailored to recurrent professional situations,  
where OZT could be problematic. A valuable contribution  
to professional education would be to discover and inculcate  
630 profession- or discipline-specific ways to avoid OZT.

### LEARNING ROUTINES FOR AVOIDING OZT

Learning routines that can help overcome OZT exhibit a  
strong focus on active understanding of new and variable  
contexts while seeking explanations and solutions that gener-  
635 alize across the stable components. Often times, these learn-  
ing routines depend on bypassing solutions that are good  
enough, yet are not optimally sensitive to context.

Even so, the development of any new learning routine  
runs the risk of OZT. For instance, teachers and students  
640 might overgeneralize guided-discovery activities to situations  
where telling first might be more appropriate. Ideally, people

would know the conditions under which one learning routine  
is more optimal than another, and when it is important to  
learn rather than just perform. Perhaps it is possible for peo-  
ple to develop a meta-routine for deciding among different  
645 learning routines across the range of contexts and outcomes  
that one might conceivably anticipate in an ever-changing  
future. Unfortunately, we know of no examples of successful  
metastrategies for selecting among learning routines.

However, there is a promising general solution for help- 650  
ing overcome OZT: Actively seek feedback. Prior to devel-  
oping a deep understanding of an endeavor and its context,  
people do not have internal models that enable them to self-  
monitor whether they are over assimilating. Without support  
for noticing, people can miss many features of their every- 655  
day experiences (e.g., Feuerstein, Feuerstein, & Falk, 2010;  
O'Mahony et al., 2012), and what they do notice can be lim-  
ited in its scope. Feedback provides an important source of  
information, because it can alert learners that their current  
routines and knowledge are suboptimal. Educators often pro- 660  
vide feedback for learning, and this is very important (e.g.,  
Black & Williams, 1998). However, people also need to de-  
velop learning routines to seek feedback rather than wait for  
it, or worse, avoid it (Ch

As an illustration, g 665  
tion of being client an  
et al., 2011; Nelson &  
tive learning routines lea  
from clients as well as from those who will be impacted  
by their designs (Atman et al., 1999). This can help block 670  
the kinds of OZT that fail to take into account new fea-  
tures, needs, and opportunities that would be missed if they  
simply used their previously acquired assumptions of what  
a good solution would be. Several design schools now use  
client- and stakeholder-centered design with their students, 675  
in the hopes that they develop feedback-driven learning rou-  
tines (e.g., Olin College of Engineering and Stanford Design  
Institute).

Outside of design, another example of feedback- 680  
seeking routines is found in Problem-Based Case Learn-  
ing (PBCL), an instructional approach that is being devel-  
oped by a group of community college leaders ([http://www.  
makinglearningreal.org](http://www.makinglearningreal.org)). PBCL involves teachers and stu-  
dents working with local small businesses to help everyone  
learn from one another (Johnson & Loring, 2012). PBCL 685  
actively connects community college instructors and students  
with small business owners and heads of other programs that  
exist in their local communities. In addition to creating a  
need to know and a reason to get it right, PBCL maintains  
constant interactions among collaborators and hence helps 690  
students and instructors realize when their proposed solu-  
tions represent negative or positive transfer through feed-  
back from client and stakeholder perspectives. We suspect  
that these types of PBCL routines will transfer, given suffi-  
695 cient experiences. For example, students in PBCL should de-  
velop the kinds of information seeking propensities and skills

before, this was treated as one  
word, but here it is two words.

insert hyphen

demonstrated in the previously discussed studies of expert designers conducted by Atman et al. (1999).

700 Is there a way that approaches like PBCL could be brought to K-12 classrooms, especially when younger students are less able to produce designs that would be embraced by clients? With some adaptation to the basic model, it seems possible. For example, in American Government courses, students can engage in simulations of political decision making 705 where students play the role of different constituents (Parker et al., 2011). To ensure that students can move beyond the assumptions they bring to their roles, experts can visit the classroom to provide “pushback.” In addition, new technologies and games provide possibilities for creating rich feedback in a variety of contexts including social studies and political science (e.g., <http://www.icivics.org>; <http://www.legsim.org>). Future research should explore novel ways of helping students learn to seek feedback, plus explore the bigger question of whether seeking feedback can become a balanced routine 715 that transfers well.

## SUMMARY

Many people have proposed that transfer is rare (e.g., Detterman, 1993; Lave, 1988). From this vantage, the question is whether it is possible to improve rates of positive transfer so that people can efficiently reuse prior learning in otherwise 720 novel situations. From another perspective, transfer is ubiquitous. There is no situation, no matter how novel, where people do not transfer in prior experiences to make some sense of that situation. From this vantage, the challenge is how to help people avoid negative transfer, so they can reduce the hold of prior knowledge to more effectively learn what is new and adapt. Both perspectives are correct. The overarching question for transfer should ask how people can strike a balance between (a) the efficiencies of seeing the “old in the new” and reusing what they know and (b) the adaptive learning that comes from seeing the “new in the old” and exploring learning opportunities that may exist. 725

The tensions of positive and negative transfer apply to organizational learning as well as individual learning. For example, the organizational theorists Levinthal and March (1993) described exploitation and exploration. Exploitation is the “the use and development of things already known,” whereas exploration is “the pursuit of knowledge, of things that may come to be known” (p. 105). Their focus involves 740 the strategic management of corporations and the kinds of organizational supports and routines put in place to balance efficiency and innovation (see also Bransford et al., 2012). In this sense, individual attitudes and learning strategies are affected by the organizational structures and goals of the company. 745

For both the organization and the individuals, issues of OZT are pervasive because it is often efficient to attempt to exploit previously successful routines but, in the process,

overlook opportunities to learn that may yield even more successful ways of proceeding. The analogy between strategic 750 management and individual learners reacting to an everyday world should not be taken too far. But mapping from the corporate world to individuals can help highlight issues that individuals face, especially regarding OZT.

The Boeing Company’s switch from aluminum planes to 755 composite planes provides a useful example for drawing out the mappings and the differences. The company had expertise and infrastructure in the development of aluminum planes, which it had successfully exploited. Nevertheless, it made a decision to explore and eventually pursue a plane made of 760 composite materials (e.g., see Stevens & Richey, 2012). This caused some short-term losses in efficiency (what Fullan, 2001, called “implementation dips”), as the company had to adapt along a number of dimensions, including how to teach 765 the employees to work with composites instead of aluminum (Lawton et al., 2012; O’Mahony et al., 2012).

One mapping involves feedback loops that inform actions and decisions. Boeing’s decision to invest in how to make a fundamentally new plane was based on strong metrics about a 770 number of issues (customer demand, the design of new materials) that signaled the need to break from the past. In contrast, many school practices do not provide the kinds of feedback opportunities that are important for adaptation—especially in our fast-changing environment. For example, many schools do not gather sufficient feedback about the performance of 775 policymakers, teachers, students, and communities—the lack of which allows individual and institutional learning routines to become entrenched.

For individuals, there often is not a set of strong routines in place for regularly seeking feedback. Hence it can be difficult to recognize that one is overrelying on prior knowledge based on what has worked in the past. From the perspective of the individual, when feedback is not naturally forthcoming, transfer can look positive when it may be negative. The importance of feedback, especially formative feedback that 785 offers opportunities for new learning, is well known (e.g., Black & Williams, 1998; NRC, 2001; Thorndike, 1913). This brings up the concern that even when feedback is provided, it can be misleading (Bransford & Schwartz, 1999). For example, students may receive positive feedback for correct answers, but they may still not notice what is new in a lesson. 790

A particularly important issue is that instruction often does not prepare students to seek feedback once they leave the orchestrated lessons and tests of school. Without learning 795 routines for seeking feedback, it is less likely that they will receive signals for when they should adapt and learn. We described several promising approaches for helping people learn to seek feedback (e.g., working with actual clients as in many design schools), but this is an area that requires more 800 research.

Another mapping between corporations and individuals involves the challenge of letting go of familiar routines and

805 knowledge that appear to be working well enough. In the Boeing case, the decision to engage in composite planes was a calculated and considered risk that factored in the likely short-term losses and costs of retooling against the projected benefits. When learners give up well-known ways of accomplishing immediate goals to pursue novelty, they also put themselves at risk. For instance, they may actually be in a situation where it would have been better to stick with the tried and true. Moreover, people must be able to handle the ambiguity that often accompanies innovation and adaptation. They must believe they can be efficacious in learning something new (Bandura, 1997) and that they are capable of changing their ways of thinking and doing (Dweck, 2000; Nolen, Ward, & Horn, 2011). Another critical factor in adapting to new situations is having the courage to persist despite initial failures (Chase, 2011). Letting go of old routines requires a disposition that can tolerate the potential perils of the new and unknown.

In sum, the literature on transfer has predominantly studied positive transfer on the assumption that it is the most efficient and rational behavior. When we add OZT to the mix, the assumption changes, so the question becomes how people strike a balance between positive transfer and overgeneralizations that block new learning. Finding the appropriate balance is difficult and typically goes beyond a learner's possible rational analysis of the available information. As such, it brings a host of new issues that range from seeking more information to developing dispositions for handling ambiguity and failure. Research on transfer would benefit by expanding its boundaries, so it is not just about how to help people get the right answer but also about how to help people to continue learning.

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# How Does Expansive Framing Promote Transfer? Several Proposed Explanations and a Research Agenda for Investigating Them

Randi A. Engle, Diane P. Lam, Xenia S. Meyer, and Sarah E. Nix

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*Randi A. Engle, Diane P. Lam, Xenia S. Meyer, and Sarah E. Nix*

# How Does Expansive Framing Promote Transfer? Several Proposed Explanations and a Research Agenda for Investigating Them

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When contexts are framed expansively, students are positioned as actively contributing to larger conversations that extend across time, places, and people. A set of recent studies provides empirical evidence that the expansive framing of contexts can foster transfer. In this article, we present five potentially complementary explanations for how expansive framing may promote transfer and outline a research agenda for further investigating them. Specifically, we propose that expansive framing may (a) foster an expectation that students will continue to use what they learn later, which may affect the learning process in ways that can promote transfer; (b) create links between learning and transfer contexts so that prior learning is viewed as relevant during potential transfer contexts; (c) encourage learners to draw on their prior knowledge during learning, which may involve them transferring in additional examples and making generalizations; (d) make learners accountable for intelligently reporting on the specific content they have authored; and (e) promote authorship as a general practice in which students learn that their role is to generate their own solutions to new problems and adapt their existing knowledge in transfer contexts.

If students are to be successful and if schooling is to have a significant impact on their lives, it is essential that students regularly transfer what they learn (Renkl, Mandl, & Gruber, 1996; Schwartz, Bransford, & Sears, 2005). Transfer occurs when “learning to participate in an activity in one situation [i.e., *learning context*] . . . influence[s] (positively or negatively) one’s ability to participate in another activity in a different situation [i.e., *transfer context*]” (Greeno, Smith, & Moore, 1993, p. 100).

In this article, we examine the idea that transfer can be promoted by the instructional practice of framing learning contexts in an expansive manner and develop several explanations for how it may do so. First, we quickly summarize the two basic ways that transfer is usually explained. We then explain what we mean by the framing of learning contexts as compared to these approaches and briefly review recent studies that provide evidence that framing indeed affects transfer. In the core of the article, we propose five potentially complementary explanations for *how* expansive framing may promote transfer, illustrating each with existing data. Finally, we

close by proposing a research agenda for further investigating these explanations.

## TWO EXISTING TYPES OF EXPLANATIONS FOR TRANSFER

In this section, we first discuss two types of explanations for transfer that are common in existing research. This then allows us to describe how the framing of learning and transfer contexts relates to these types of explanations in the rest of this article.

### Explanations for Transfer That Focus on Content

Most research on explaining transfer focuses in some way on the substantive content that learners are to transfer (Mestre, 2003; Reeves & Weisberg, 1994; Schwartz & Nasir, 2003). For example, the classic paper by Gick and Holyoak (1983) provided evidence for their hypothesis that “the induction of a general schema from concrete analogs will facilitate analogical transfer” (p. 1). Their general idea was that learners are more likely to apply what they have learned from one analogical problem to another if they form a content-based

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add "we" before "develop",  
AND a comma before "and  
we develop"

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Q1  
Q2

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60 generalization (a.k.a. “schema”) at the appropriate level of  
 abstraction such that it can be applied to a new problem. Gick  
 and Holyoak (1980, 1983) illustrated this idea in a series of  
 clever experiments in which learners were more or less likely  
 to transfer a prior solution to analogous problems depending  
 65 on the degree of support they were provided for inducing  
 such generalizations. Subsequent research has provided ad-  
 ditional evidence for the importance of forming such gener-  
 alizations (e.g., see Chi & VanLehn, this issue/2012; Gentner,  
 Loewenstein, & Thompson, 2003; Reeves & Weisberg, 1994;  
 70 Rittle-Johnson & Star, 2007), with recent research showing  
 how instructional interactions can lead learners to focus on  
 making certain kinds of generalizations rather than others  
 (Lobato, Ellis, & Muñoz, 1999).

Since then, most research on explaining transfer has fo-  
 75 cused, in one way or another, on the substantive content  
 that we hope learners will be able to transfer. In addition  
 to the importance of content-based generalizations, there  
 is a consensus that the most fundamental prerequisite for  
 transfer is that the particular content to be transferred has  
 80 been learned in a sufficiently deep, strong, and lasting way  
 (Bransford, Brown, & Cocking, 1999. see also Chi & Van-  
 Lehn, this issue/2012). Second, comparing multiple exam-  
 ples and nonexamples of a potentially transferable idea has  
 been found to be particularly important for inducing three  
 85 transfer mechanisms: (a) constructing appropriate general-  
 izations (e.g., Chang, 2006; Gick & Holyoak, 1983; Gen-  
 tner et al., 2003; Goldstone, Landy, & Son, 2009; Gold-  
 stone & Wilensky, 2008; Ming, 2009; Richland, Stigler, &  
 Holyoak, this issue/2012; Rittle-Johnson & Star, 2007) and  
 90 (b) forming useful mappings between the examples and gen-  
 eralizations (e.g., Goldstone & Wilensky, 2008; Reeves &  
 Weisberg, 1994; Wagner, 2006), and (c) constructing map-  
 pings between examples as part of analogical reasoning  
 (Holyoak, 2005; Reed, in press). All of these mechanisms aid  
 95 transfer and affect exactly what particular content is trans-  
 ferred. Finally, it has been shown that specific, content-based  
 hints to use prior learning enhance transfer by specifying the  
 particular pieces(s) of knowledge to be used and encouraging  
 students to immediately apply it to solve a particular prob-  
 100 lem (Anolli, Antonietti, Crisafulli, & Cantoia, 2001; Campi-  
 one & Brown, 1984; Catrambone & Holyoak, 1989; Gick &  
 Holyoak, 1980, 1983; Reed, Ernst, & Banarji, 1974; Spencer  
 & Weisberg, 1986). Although different in many other ways,  
 all of these explanations for transfer—learning the content-  
 105 to-be-transferred more effectively, comparing multiple exam-  
 ples, forming content-based generalizations, and responding  
 to content-based hints—focus in one way or another on the  
 substantive content to be learned and hopefully transferred.

In general, content-based explanations for transfer have  
 110 the following basic form (see top of Figure 1). First there  
 is either an explicit or implicit effort to decontextualize<sup>1</sup> the

social context (Step 1) by either removing it as a potential  
 distraction (explicit) or simply by focusing exclusively on  
 the content (implicit). Then, learning of the content to be  
 transferred occurs (Step 2). As part of this, whatever content-  
 115 based mechanisms for fostering transfer are also used (Step  
 3). Finally, this leads to successful transfer of that content  
 (Step 4).

### Explanations for Transfer That Focus on Physical Aspects of Contexts

In contrast to content considerations, issues of context have  
 been underemphasized in most transfer research. When con-  
 text is addressed in research on transfer mechanisms, it is  
 primarily treated as a physical reality. In this conceptual-  
 125 ization, the *context* includes features that could be captured  
 in a photograph including where a learning or transfer ses-  
 sion is being conducted, when it occurs, and who and what  
 is present (Barnett & Ceci, 2002; Catrambone & Holyoak,  
 1989; Reeves & Weisberg, 1994; Spencer & Weisberg, 1986;  
 Thorndike, 1903/2009). The consensus of empirical research  
 130 into the effect of physical contexts on transfer is that the  
 likelihood of transfer increases the more that such physical  
 features overlap between learning and transfer contexts (Bar-  
 nett & Ceci, 2002; Catrambone & Holyoak, 1989; Reeves &  
 Weisberg, 1994; Ross, 1984; Spencer & Weisberg, 1986).  
 135 This finding has been explained in classical cognitive ac-  
 counts by the idea that contextual features are stored in  
 memory along with the content being learned so that similar  
 contextual features in a transfer context end up priming or  
 cueing recall of the associated content (Anderson & Bower,  
 140 1973; Godden & Baddeley, 1975, 1980; Reeves & Weis-  
 berg, 1994; Ross, 1984; Smith, Glenberg, & Bjork, 1978;  
 Tulving & Thomson, 1973). In physical context-based ac-  
 counts, there are four steps to successful transfer (middle of  
 145 Figure 1):

1. Associating the physical context at learning with the  
 content to be learned;
2. Learning that content;
3. Noticing physical similarities between the learning and  
 transfer contexts; and
- 150 4. Successfully transferring the content because of the  
 content being cued or primed by the physical features  
 of the transfer content.

and other school-like problems are sometimes expressed (e.g., Goldstone &  
 Wilensky, 2008; Wagner, 2006). Instead, social context is the socially estab-  
 lished who, when, where, how, and why of a learning or transfer situation.  
 Given that, in this article, “decontextualization” means somehow removing  
 this surrounding social context so that only the “content” to be learned and  
 (we hope) transferred remains. Part of what would remain after this kind of  
 decontextualization would be any associated problem contexts.

<sup>1</sup>We want to make it clear that when we say “social context” we are not  
 referring to “problem contexts,” the cover stories in which mathematical

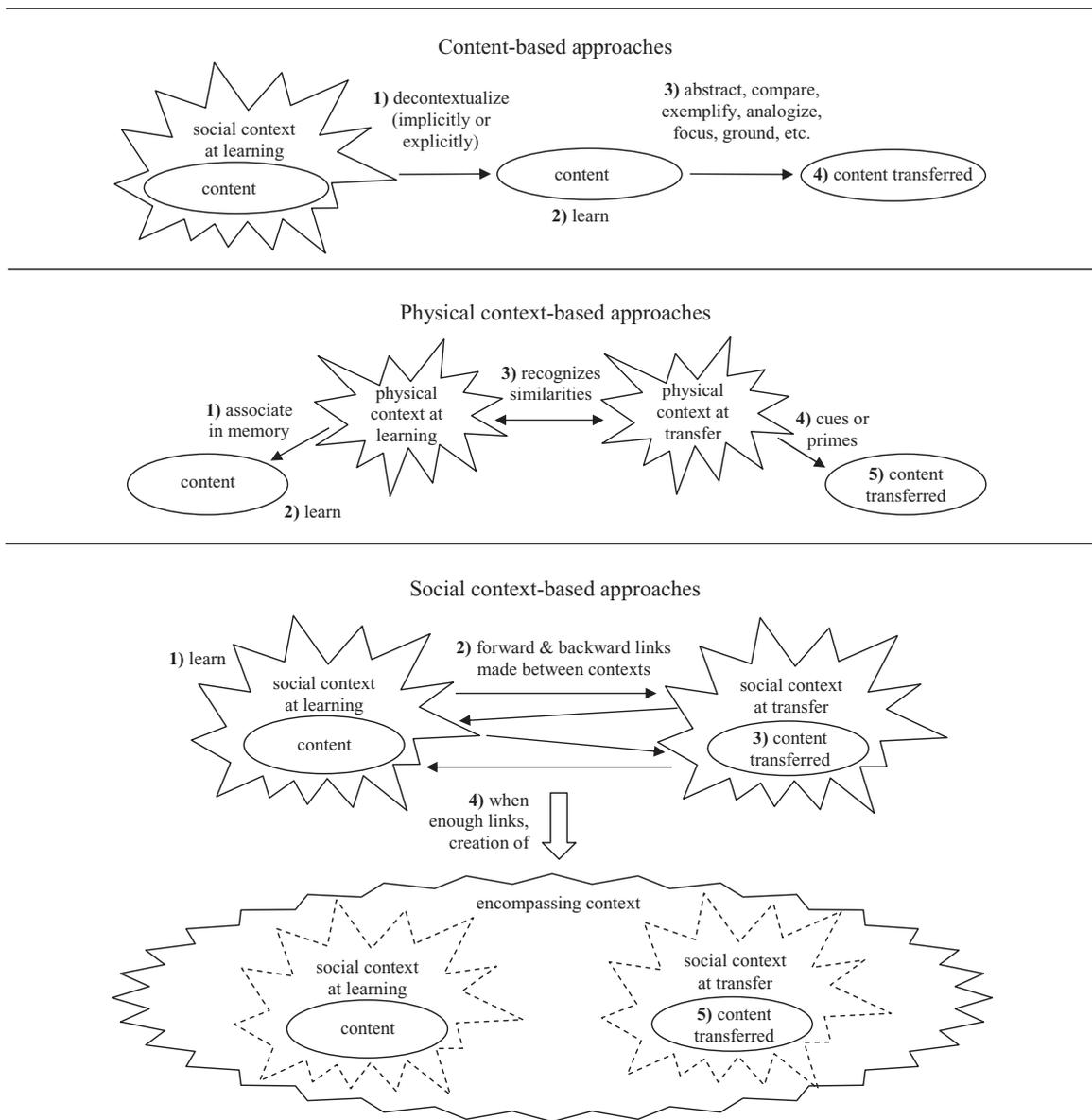


FIGURE 1 Diagrammatic comparisons of three approaches to explaining and fostering transfer.

FRAMING SOCIAL CONTEXTS AS AN INSTRUCTIONAL PRACTICE THAT AFFECTS TRANSFER

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In our research on framing contexts and transfer, we instead conceptualize contexts as social realities (Searle, 1995). Our claim is that learning and transfer contexts can be socially framed in different ways and that this will then influence students' propensity to transfer what they learn (Engle, 2006b; Engle, Nguyen, & Mendelson, 2011). Framing is the meta-communicative act of characterizing what is happening in a given context and how different people are participating in it (Bateson, 1972; Goffman, 1974; Goodwin & Duranti, 1992; Kelly & Chen, 1999; Tannen, 1993). For ex-

ample, a teacher can frame a lesson as a one-time event of learning something that students are unlikely to ever use again, or as an initial discussion of an issue that students will be actively engaging with throughout their lives. Our contention is that the first kind of framing, which we refer to as *bounded*, will tend to discourage students from later using what they learn, while the second, which we refer to as *expansive*, will tend to encourage it. Thus, in our view, which builds upon earlier situative and socio-cultural theorizing on transfer (Greeno et al., 1993; Laboratory for Comparative Human Cognition [LCHC], 1983; Lave, 1988; Pea, 1987), it is not just the physical aspects of a context that matter for transfer (Barnett & Ceci, 2002; Catrambone & Holyoak, 1989; Reeves & Weisberg, 180

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1994; Spencer & Weisberg, 1986), but also how social interactions frame learning and transfer contexts as particular kinds of social realities (Gee & Green, 1998; Searle, 1995).

From this perspective, the reason that contexts matter for transfer is that content knowledge is inextricably tied with its contexts of use (Greeno et al., 1993; LCHC, 1983; Lave, 1988; Pea, 1987) as shown in the bottom of Figure 1. Accordingly, how a context is framed ends up having profound effects on whether and how its associated content knowledge is used elsewhere. Specifically, transfer is encouraged to the extent that a learning context and therefore the content learned within it (Step 1) can be recognized as providing resources for productive action in potential future transfer contexts (Engle, 2006b; cf. Hammer, Elby, Scherr, & Redish, 2005). Complementarily, transfer is also encouraged to the extent that transfer contexts are framed as being connected back to past learning contexts (Pea, 1987). Both kinds of framing links—forward in time from learning contexts to potential transfer contexts or backward in time from transfer contexts to prior learning contexts (Step 2)—create what is referred to as intercontextuality between learning and transfer contexts (Beach & Phinney, 1998; Bloome, Power Carter, Morton Christian, Otto, & Shuart-Faris, 2005; Floriani, 1994; Gee & Green, 1998; Leander, 2001; Putney, Green, Dixon, Duran, & Yeager, 2000). This intercontextuality then fosters transfer between the linked learning and transfer contexts (Step 3). When enough links between learning and transfer contexts are made, the degree of intercontextuality can get so strong that a larger encompassing context is formed that seamlessly incorporates learning and transfer contexts (see Step 4 in bottom of Figure 1; Greeno et al., 1993). As a result, further transfer is promoted (Step 5). In contrast to transfer after specific links are made between learning and transfer contexts (Step 3), this time learners are not aware that they are transferring anything as to them they are simply continuing to use the same relevant knowledge within the same (larger) context (Greeno et al., 1993; Lave, 1988; LCHC, 1983).

We believe that there are several different aspects of learning contexts that can be framed to affect transfer. This article focuses on framing that is expansive versus bounded with respect to settings and roles. Because settings comprise times, places, and participants, an expansive framing of a learning setting may extend it to include the past and the future, different places, and additional people. Conversely, an extremely bounded framing of a learning setting may constrain it solely to a short span of the present time, a small part of the available physical space, and just one or two of the people that are physically present.

Framing may also be negotiated around the roles of learners. In an expansive framing of roles, learners are positioned as active participants in a learning context where they serve as authors of their own ideas and respondents to the ideas of others. Within this sort of learning environment, students' authored ideas are recognized and integrated into class discussions and other activities (e.g., Mercer, 1995). In contrast,

in a bounded framing of roles, learners may be positioned on the periphery of a learning context, where, rather than sharing their own ideas, they are expected to report on their learning about the ideas of others, such as those presented by a text or a teacher. As active participants in a learning context, expansively framing learners “crucially make[s] use of the fact that the one form of intercontextuality that always exists between learning and transfer contexts is the presence of the same learner” (Engle, 2006b, p. 457).

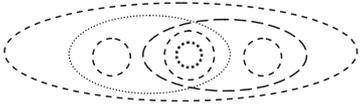
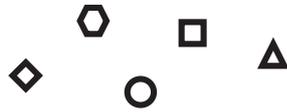
We further specify these contrasting ways of framing in Table 1, which shows how we successfully operationalized these two distinct ways of framing in a one-on-one tutoring experiment (Engle et al., 2011). More bounded or more expansive frames were proposed by a tutor for each participating student, with the framing negotiated between the tutor and student until the student typically acceded to the tutor's proposed framing. In the expansively framed tutoring sessions, students were positioned as integral parts of a university-based learning environment involving a larger research team and were credited for having their own ideas about the topics being discussed in text and diagrams. In contrast, in the tutoring sessions with the bounded framing, tutors narrowly circumscribed the time, place, and participant aspects of settings to here and now and positioned the role of the learners as disconnected reporters of the text and diagrams' ideas. Further, these sessions were also framed as a private matter between each tutor and the student and were restricted to each particular learning session and part of the room. Responses from student surveys and interviews revealed how students perceived and responded to the framing. These data showed that the framing manipulations, based on the contrasts shown in Table 1, were successful.

#### EVIDENCE THAT FRAMING CONTEXTS AFFECTS TRANSFER

A growing series of studies have empirically investigated connections between the framing of contexts and transfer. Two recent experiments systematically tested one or more aspects of this general hypothesis and four classroom research studies provide complementary evidence that transfer may be affected by framing.

The first known experiment related to framing and transfer was conducted by Hart and Albarracín (2009, Experiment 2). They showed that people are more likely to repeat an action they have just engaged in—the most basic form of transfer that there is (cf. Salomon & Perkins 1989)—if they are prompted to describe it using a progressive verb aspect that frames it as a continuing activity (“I was doing . . .”) versus a perfective aspect that frames it as a completed action (“I did . . .”). Engle et al. (2011) then created the tutoring experiment, framing manipulation of which was illustrated in Table 1. They showed that students being tutored with an expansive, versus a bounded, framing were about twice as likely

TABLE 1  
Operationalization of Expansive Versus Bounded Framing in the Tutoring Experiment

Aspects of Contexts That Can Be Framed	Expansive Framing  (Shown to Promote Transfer)	Bounded Framing  (Shown to Discourage Transfer)
Setting:	Ask student to specify other settings in which the topic(s) have, are, or will be likely to come up in their lives	Do not ask student to specify other settings in which the topic has, is, or will be likely to come up in their lives
• Time	<ul style="list-style-type: none"> <li>• Refer to the study as a whole as including both days</li> <li>• Refer to other times, both inside and outside of the experiment</li> <li>• Use present progressive verbs (“you’re figuring out”)</li> </ul>	<ul style="list-style-type: none"> <li>• Refer to each part of each day’s session as a separate event</li> <li>• Make no references to times other than the just completed present</li> <li>• Use simple past with completion verbs (“we’re finished with that now”)</li> </ul>
• Place	<ul style="list-style-type: none"> <li>• Frame location as at a university</li> <li>• Refer to other places—their home, school, doctor’s office, etc.—in which they can use what they’re learning</li> </ul>	<ul style="list-style-type: none"> <li>• Frame location as this specific room</li> <li>• Do not make references to other places outside of the room</li> </ul>
• Participants	<ul style="list-style-type: none"> <li>• Treat larger activity as involving the student, you and the rest of the study team, plus their family, friends, teachers, and anyone else they mention above</li> <li>• Ask student how they would explain their ideas to the other people they mentioned as part of the settings</li> <li>• When students show understanding of one of the key ideas, note that they can now explain that to whoever they mentioned as an audience</li> </ul>	<ul style="list-style-type: none"> <li>• Treat tutoring event as a private matter involving only you and the student, and not other members of study team or other people they know</li> <li>• Have student explain the text’s ideas to you just as often and as extensively as in the expansive condition</li> <li>• When students show understanding of one of the key ideas, note that they have properly represented what the text said</li> </ul>
Roles	<ul style="list-style-type: none"> <li>• Ask student to explain their own evolving ideas about the system using the text sentences as a resource.</li> <li>• Revoice student’s explanations, crediting student with authorship and checking with them about whether you reformulated their ideas accurately.</li> </ul>	<ul style="list-style-type: none"> <li>• Ask student to explain what the text has said about the system in each sentence.</li> <li>• Reformulate what student said as what the text has presented, not giving them an opportunity to correct as the reformulation should be accurate.</li> </ul>

Note. Adapted under Creative Commons Attribution license from “The Influence of Framing on Transfer: Initial Evidence From a Tutoring Experiment,” by R. A. Engle, P. D. Nguyen, & A. Mendelson, 2011, *Instructional Science*, 39, p. 612. Copyright 2011 by R. A. Engle, P. D. Nguyen, & A. Mendelson.

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to appropriately transfer facts, a conceptual principle, and a learning strategy from one human body system to another.

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In the first classroom study related to framing and its effects on transfer, Hammer et al. (2005) found that when two transfer contexts were reframed as having to do with active student sense making rather than simply the replication of knowledge, students were more likely to “transfer-in” (Schwartz et al., 2005) their prior knowledge in ways that helped them understand new physics concepts. Engle (2006a, 2006b) then presented a case of successful classroom transfer that could not be explained by considering only content-based supports for transfer. She showed how this case of transfer could be explained by also considering the teacher’s framing of the learning context. This teacher expansively framed her interactions with her fifth-grade students studying endangered species by (a) temporally connecting to prior and future interactions in which students could use what they were learning, and (b) positioning students as contributing to a larger community of people interested in what they were learning about. A more recent classroom case study illustrated how a high school biology teacher expansively framed his classroom by (a) making links to settings outside of school; (b) extending temporal horizons to the past, where content was

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learned, and to the future, where it remains relevant; (c) connecting curriculum units across time; (d) training students to make connections across topics (cf. Richland et al., 2012/this issue); and (e) positioning students as part of a larger learning community (Engle, Meyer, Clark, White, & Mendelson, 2010; Meyer, Mendelson, Engle, & Clark, in preparation). These students scored well on researcher-designed transfer tests as well as on end-of-year standardized tests. Finally, showing that framing matters for subjects other than science, Mendelson (2010) found that student transfer of linguistic forms from online to in-person, second language learning contexts was supported by an instructor’s expansive framing, where text-based forum activities were framed as being connected to later in-class, face-to-face discussions.

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HYPOTHESIZED EXPLANATIONS FOR HOW FRAMING CONTEXTS MAY AFFECT TRANSFER 325

Although prior research has shown that framing contexts differently can affect transfer, it has not explained exactly *how* this process occurs. In this section, we propose five potential

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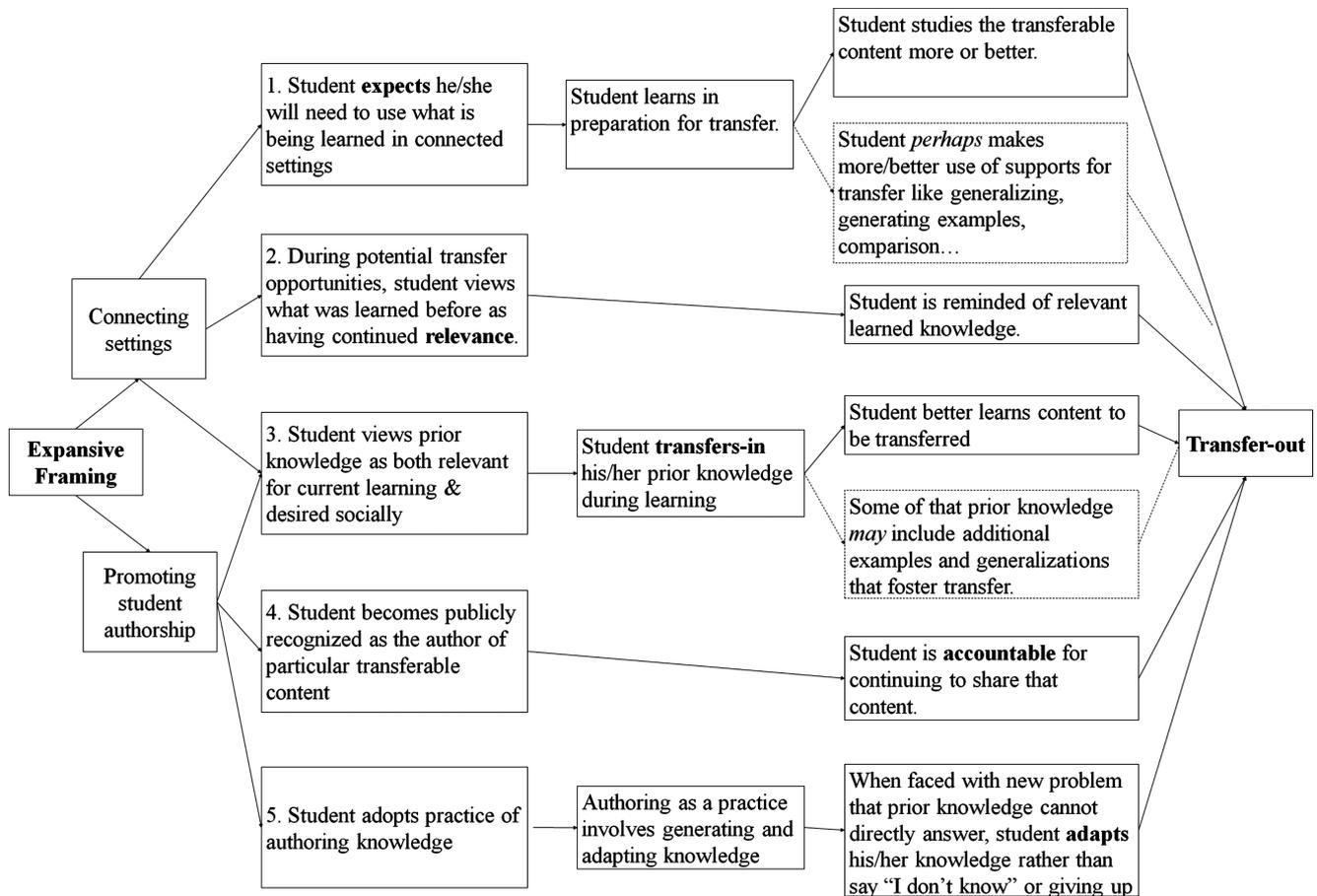


FIGURE 2 Five potential explanations for how expansive framing may foster transfer. *Note.* Dashed arrows and boxes indicate processes that may or may not occur depending on what content-based supports for transfer are available.

335 explanations for how expansive framing may promote transfer (see Figure 2). Each explanation describes a different series of processes through which expansive framing may lead to transfer. In some cases, these effects are partly mediated by other already documented transfer mechanisms.

It is important to note that these explanations are not mutually exclusive and may even be complementary. Thus, an account of how transfer was promoted by expansive framing for any particular student may involve all five, just one, or any other combination of these explanations.

340 We first preview each explanation by describing it with reference to relevant literature. We then characterize each set of explanatory processes in more detail by drawing on our existing data from two prior studies of expansively framed classrooms (Engle, 2006b; Engle et al., 2010; Meyer et al., 345 in preparation) as well as the tutoring experiment (Engle et al., 2011).

### OVERVIEW OF EACH EXPLANATION

350 Each proposed process for explaining how expansive framing promotes transfer is prompted by one or two aspects of a

full expansive framing. Given that, we first introduce two explanatory processes that begin by *connecting settings* with each other. We then discuss one explanation that is initiated by both connecting settings and *promoting student authorship*. Finally, we consider two explanations that are started simply 355 by promoting student authorship.

First, we propose that expansive framing can create *connections between settings* for learners, in which knowledge that is relevant in one setting is recognized as also relevant in other settings, a key aspect of intercontextuality. Connecting 360 settings with each other encourages transfer: (a) during learning, when students *expect* they will later need to transfer what they are learning and may be more likely to *prepare* for this possibility, and (b) during potential transfer contexts, when students view prior content as *continuing to be relevant* 365 (Leander, 2001; Pea, 1987; Ross, 1984). These first two explanations and their processes are laid out in the trajectories shown in Figure 2.

With respect to the first explanation, existing literature about transfer has already recognized that transfer can be 370 promoted by creating an *expectation* for transfer in which students see that what they are learning will maintain

relevance over time (e.g., Bereiter, 1995; Brown, 1989). This notion is closely related to the concept of *utility value*, or the degree to which a task is perceived as being relevant beyond the immediate situation (Hulleman, Durik, Schweigert, & Harackiewicz, 2008). It is also related to Pugh and colleagues' (2010) finding that transfer can be promoted in part by framing curricular content as having the potential for transforming students' everyday experiences. This article adds to these prior literatures by explaining how framing settings as connected may foster such an expectation for transfer and showing how it initiates a series of processes that eventually lead to greater transfer.

Fostering an expectation for future transfer by having teachers connect learning settings with future settings in which transfer is desired may lead students to study what they are learning about in potentially more effective ways that support transfer. At the most basic level, students who expect they will need to continue using what they have learned may prepare for such future use. They are likely to study that material more often and more intensively, which may result in more enduring memory representations that students can draw upon during later transfer tasks. This general idea is consistent with findings from motivational research that shows that students who perceive classroom tasks as having a higher utility value both report that they expend more effort in their science classes (Cole, Bergin, & Whittaker, 2008; Mac Iver, Stipek, & Daniels, 1991) and perform better in them (Bong, 2001; Hulleman et al., 2008; Malka & Covington, 2005; Simons, Dewitte, & Lens, 2003).

Such expectations for transfer may have an even greater impact on transfer to the extent that individual students are aware of and able to use content-based strategies for enhancing transfer like generating examples, comparing them, constructing generalizations, and becoming sensitive to the applicability conditions of examples and generalizations (e.g., Gick & Holyoak, 1983; Gentner et al., 2003; Renkl et al., 1996; Wagner, 2006).<sup>2</sup> For example, research has already shown that when students have the expectation that what they are learning will continue being relevant, they put more effort into becoming sensitive to the specific features of examples that make them suitable for applying relevant generalizations (Gilbert et al., 2011; Keiler, 2007). In effect, the expansive framing of settings may make students more likely to use content-based supports for transfer as part of preparing for expected future transfer events (Engle, 2006b).

Turning to Explanation 2 (again see Figure 2), an expansively framed learning environment may also increase the likelihood that, in a potential transfer context, students view what they learned before as having *continued relevance* (Clark, 1996; Leander, 2001). Consequently, students are more likely to be reminded of relevant learned knowledge from the prior learning context (Ross, 1984) and be inclined

to use it, especially if the learning context has been positioned as continuing to have socially desirable knowledge resources (Pea, 1987). As Pea (1987) explained, transfer is promoted when a student is socially influenced to construct "a 'reading' of a problem situation as one for which transfer of previous knowledge is possible, or important, or worth the effort" (p. 655). Thus, by creating links back to prior learning contexts, the expansive framing of past settings may encourage students to make use of transfer opportunities by using their relevant learned knowledge.

The third explanation relies on both framing a learning setting as being connected to prior ones and on framing roles by positioning students as authors of their own ideas (again refer to Figure 2). Both types of framing are likely to lead students to view their own prior knowledge as relevant to current learning, encouraging them to "*transfer-in*" (Schwartz et al., 2005) *more of their prior knowledge during learning* as they construct new understandings. Drawing on prior knowledge in this way generally enhances the quality of initial learning, which is necessary for later transfer-out to new contexts (e.g., Bransford et al., 1999). In drawing more extensively on their prior knowledge, students may also potentially transfer-in additional examples and generalizations related to what they are learning about, which prior research has shown specifically enhances transfer (e.g., Gick & Holyoak, 1980, 1983; Reeves & Weisberg, 1994; Salomon & Perkins, 1989). These examples and generalizations then can provide additional resources that could allow the student to make comparisons between examples (e.g., Chang, 2006; Gentner et al., 2003; Rittle-Johnson & Star, 2007) or consider when examples are most applicable (e.g., Renkl et al., 1996), additional content-based ways in which transfer can be promoted.

Our fourth explanation (Figure 2) hypothesizes is that by itself authorship may foster *student accountability to particular content*, which then makes students more likely to use this content in transfer contexts. Just like authors of academic papers, individual students become identified with and then are held accountable for, comment on the specific content they have authored (Engle, 2006b; Greeno, 2006; Jacoby & Gonzales, 1991). This accountability then increases opportunities and other people's expectations for them to continue sharing what they know about that topic and related topics in additional settings (Bereiter, 1995; Engle, 2006b; Greeno, 2006). In fact, students may purposely engage more frequently with contexts in which they can use the knowledge they have become identified with, sometimes even helping to construct new settings in which they can use their knowledge (Bereiter, 1995). Thus the identification of particular students with particular topics provides social opportunities and expectations that students will transfer what they know about those topics in situations that ask them to draw on their expertise (Brown et al., 1993).<sup>3</sup>

<sup>2</sup>Because processes may or may not occur in particular cases, a dashed line surrounds the box that encloses them.

<sup>3</sup>We note that this explanation differs from Explanation 1, an expectation for transfer, as the expectation for transfer is more of an individual internal

Finally our fifth explanation (Figure 2 again) proposes that if authorship becomes a general practice that students regularly participate in, it may promote the practices of *generating new knowledge and engaging in adaptive problem solving* (Hatano & Inagaki, 1986; Hatano & Oura, 2003; Schwartz et al., 2005; Schwartz, Chase, & Bransford, 2012/*this issue*). Students may then be more likely to transfer their knowledge when confronted with a completely novel problem situation, because part of the role of being someone who regularly authors knowledge is to generate reasonable responses; in effect, this *adapt their prior knowledge* (Boaler, 2002; Greeno, 2006). This response contrasts with students who respond to a transfer problem for which they do not have an obvious solution by either saying “I don’t know” or complaining about the unfairness of a question whose answer or exact solution methods have not been taught to them (Boaler, 2002).

Although as we discuss later there are undoubtedly complex relationships between these five potential explanations for how expansive framing promotes transfer, the primary goal of this article is to distinguish between the explanations. This differentiation will provide a foundation for being able to systematically investigate the explanations in future research. To advance that agenda we now characterize the five explanations in more detail using examples from our existing data.

insert comma

#### EXPLANATION 1: CONNECTING SETTINGS PROMOTES AN EXPECTATION FOR FUTURE TRANSFER

The framing of learning contexts in an expansive manner makes it more likely that students will develop an expectation that they will need to transfer what they are currently learning into the future, which then encourages them to prepare for that future use. Our ongoing research in an expansively framed high school biology classroom<sup>4</sup> provides an example of this expectation. For example, the teacher, Mr. Kent, used expansive framing on a day that the chemistry teacher visited his class (along with a range of additional pedagogical strategies for fostering transfer that were probably working concurrently with this framing). He set up the expectation that students would need to transfer what they were learning during Biology class to their future Chemistry class. Mr. Kent referred to a future setting when the students would be in Mr. Brown’s Chemistry class, and said,

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one and this involves social expectations. Also an individual expectation for transfer arises from settings being framed as connected and this social expectation for transfer arises from students being framed as authors of particular content that they have learned.

<sup>4</sup>This is the same teacher who was analyzed in Engle et al. (2010), but the teacher’s practices have become more expansively framed in several ways from collaborating with the researchers and learning about their findings.

move this whole parenthetical phrase to after “framing” because it modifies “framing” not “his class”

Most of you . . . will next year have Mr. Brown. This is Mr. Brown. He’s our Chemistry teacher for Health and Medicine. So you guys will have him for chemistry next year. . . . The reason that I’m so [strict] about things like lab safety, no open-toed shoes, data charts, accurate measurements, is because . . . this guy expects you to walk into his class on the very first day of school being able to do this. He cannot afford, in Chemistry, to spend time teaching you this. So if I’m just a nice guy and let you go . . . you’re gonna get to his class and start off [week] 1, week 2 with a D because you can’t do this, and then he’s gonna be upset because he wants you to do well. I’m gonna be upset because he’s gonna come back and say “Didn’t you teach them anything?” . . . This is why we’re so adamant about you guys doing it right.

In this example, by connecting laboratory settings across the two classes, Mr. Kent made it more likely that his students would develop an expectation that they will need to transfer what they would learn about conducting labs in Biology class to their future Chemistry class. Our contention is that this expectation may easily have motivated his students to learn lab safety more effectively in order to prepare for that future transfer.

We then found evidence that Mr. Kent’s students tended to notice this kind of expansive framing of time and also developed an expectation that what they were learning now would be needed in the future. Student surveys were used to detect the extent to which students perceived this aspect of the teacher’s expansive framing of time, and to what extent they reported that they believed that what they were learning would be useful in the future. Students were first asked, “During a typical biology class, how often does your *teacher* tell you that what you are learning might be useful . . .” at various times in the future. Student survey data indicated that students generally recognized that Mr. Kent *often* told them that what they were learning would be useful the next day, in the next few weeks, in the next year, and beyond (see leftmost bars in Figure 3).

Students were then asked, “During a typical biology class, how often do *you* think what you are learning might be useful . . .” at various times in the future. Student responses to this survey question indicated that students had also developed expectations that what they were learning would *often* be useful at various timepoints in the future (see rightmost bars in Figure 3). Our claim from this survey data is that Mr. Kent’s expansive framing may have caused many of his students to develop an *expectation for future transfer* that was equivalent with, or perhaps even stronger than, the degree to which they noticed the teacher emphasizing future usefulness. Further investigation is needed to determine how, if at all, students changed their studying and other learning habits to prepare for that transfer.

Although data from a comparison classroom that employs a bounded framing are not yet available, these data provide initial evidence consistent with the first explanation that the expansive framing of settings can lead students to develop

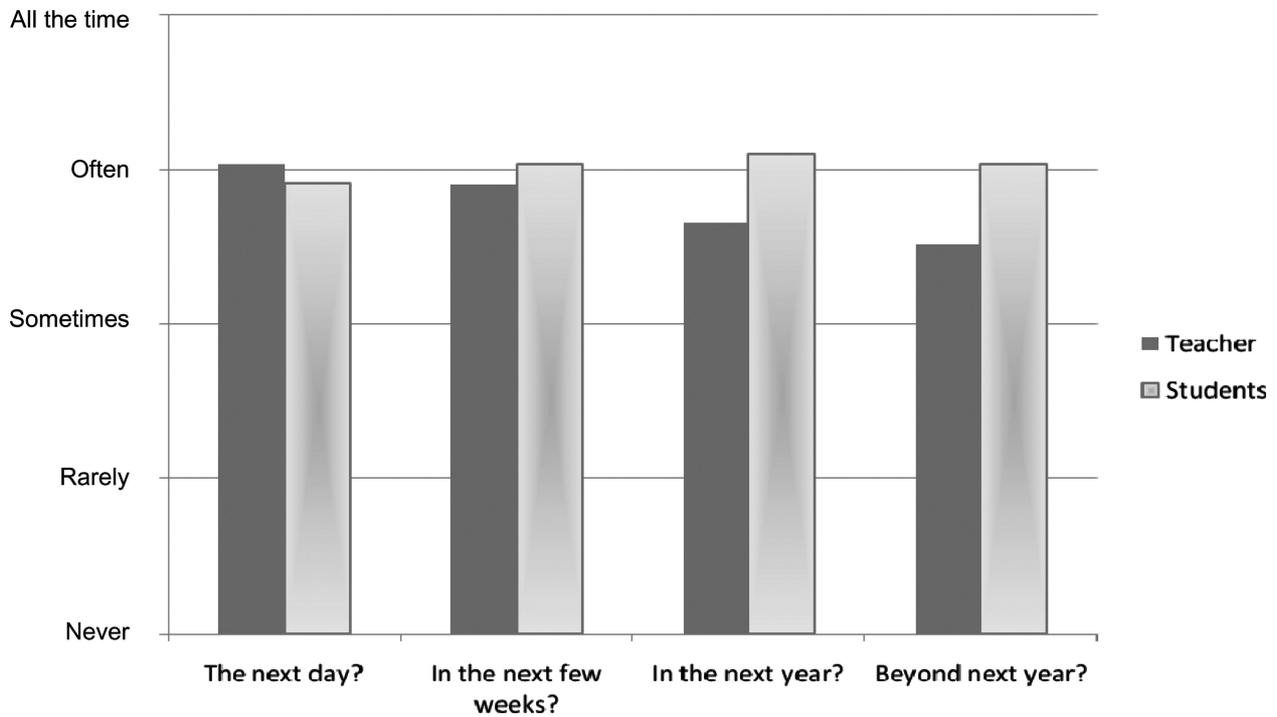


FIGURE 3 Average student perceptions of frequency of teacher telling students what they are learning will be useful the future, and student reports about how often they think what they are learning will be useful in the future.

580 expectations for future transfer. We further offer that this expectation may increase the likelihood that students will study content more often or more deeply. This may potentially also involve students taking better advantage of any content-based supports for transfer that are available in their learning environment.

585 **EXPLANATION 2: CONNECTING SETTINGS MEANS PRIOR CONTENT CONTINUES BEING RELEVANT IN POTENTIAL TRANSFER CONTEXTS**

590 Findings from the same classroom just described (Engle et al., 2010) also support the viability of the hypothesis that connecting settings fosters transfer by making it more likely that students will view their prior knowledge as being relevant, thus increasing the likelihood that they will be reminded of it during transfer opportunities. One example of connecting to prior settings during potential transfer opportunities was seen when Mr. Kent emphasized the importance of students making connections in their current laboratory work to prior class discussions and homework (Meyer et al., in preparation, 595 p. 13):

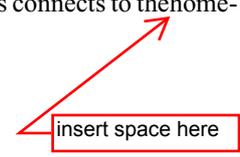
600 You have to connect what's going on in lab to what's going on in class. . . . When I'm in lab, I am always thinking, "What is this lab teaching me about what we're discussing?" . . . So when you're in lab today—what is it that we're doing in

lab, that connects to what our homework was about this past weekend?

605 It is important to note that expansive framing across time, places, and activities differs from ideas about both practicing transfer and providing content-based hints. In this example, Mr. Kent broadly spoke about the idea of students making connections between the lab setting and other course-related settings like class discussions and doing homework. Although there is a family resemblance, this is very different from providing hints to students about specific content connections they should make as it is less specific and less focused on particular content. Instead, this teacher expanded the relevance of what his students were learning across different settings, a practice that was common in his classroom instruction. However, in asking students to specifically think about how what they were doing in lab connected to their prior homework assignment, Mr. Kent also employed the more basic transfer mechanism of asking students to practice transfer. Although practicing transfer is not part of expansive framing per se, Mr. Kent's request served to make it clear that he expected them to try to transfer what they had learned from any settings he had connected to the current one. 610 615 620

625 During that same lab, we observed students responding to Mr. Kent's instruction by trying to transfer in knowledge from their prior classwork, as in the following excerpt:

Student 1: How do you think this connects to the homework?



Student 2: That is how, like, light reaction happens.  
 Student 1: Dark and light?  
 Student 2: Yeah.

Thus, Mr. Kent’s connection of the current lab setting to prior activities potentially prompted students to transfer what they had learned during those earlier activities. As the course proceeded, students continued to make connections without Mr. Kent’s prompting. This process occurred because students may have begun to see lab and classroom settings as being interconnected perhaps as a result of Mr. Kent’s expansive framing of these particular settings.

These initial analyses of Mr. Kent’s instruction are also consistent with our second explanation that expansive framing causes students to view learned knowledge as having ongoing relevance across settings. We hypothesize that with this view, students are more likely to be reminded of relevant learned knowledge in potential transfer contexts, which will, in turn, increase their propensity to transfer this learned content.

**EXPLANATION 3: AUTHORSHIP AND CONNECTING TO PRIOR SETTINGS DURING LEARNING LEADS TO TRANSFER-IN OF PRIOR KNOWLEDGE IN WAYS THAT SUPPORT LATER TRANSFER-OUT**

The third explanation hypothesizes that in an expansive environment, one in which students are positioned as authors whose knowledge from prior settings is considered welcome, students are more likely to transfer-in knowledge during learning in ways that can enhance later transfer-out. In our tutoring experiment (Engle et al., 2011), we found students transferring-in prior knowledge in ways that would be expected to enhance transfer-out. These students, who were all in the expansive framing condition in which both authorship and connecting to past settings was supported (see Figure 2), sometimes brought in their own outside examples to form generalizations about the topics they were learning. Data showed that these students were also more likely to transfer certain facts, principles, and a learning strategy to a new context.

For example, one student in the expansively framed condition transferred-in his own example of the structure of

a school to generalize his understanding of the structure of the heart: 675

How is the heart structured? The name atrium . . . it reminds me of all schools . . . like my school has a big atrium . . . kinda big. [*motions “big” with his hands*] and [it’s] someplace you go and it separates out to all the classes. So I guess you can kinda picture that. [*Tutor nods*] You can store all the stuff in the atrium before it goes out to the right place. 675

By being positioned as an author whose past knowledge was relevant, this student was in effect encouraged to transfer-in whatever he already knew that could be relevant for his learning. In comparing the heart’s structure with his school’s architecture, he was able to make the generalization that both kinds of atriums store things (students or blood) before distributing them to the next place. With this generalization supporting his learning, this student then successfully transferred what he had learned about the circulatory system to later transfer assessments about the respiratory system. 680 685

Given that the sample size for the tutoring study was not particularly large, it was reassuring to find evidence of a similar dynamic occurring in Mr. Kent’s biology class (Meyer et al., 2011). Like tutors in the expansive framing condition, Mr. Kent also positioned students as authors of their own learning and made connections with prior settings. Furthermore, survey data show that students in this class tended to transfer-in their prior knowledge. Specifically, students reported that during a typical biology class they often transferred-in ideas they already knew from the previous few days and weeks and sometimes transferred-in ideas they already knew from within the past year or longer than a year before (see Table 2). Although comparisons to bounded classrooms would be informative, these results are consistent with the idea that in an expansively framed classroom, students may be likely to transfer-in ideas from prior learning, which would then improve the quality of their learning in ways that would promote transfer-out later. 690 Q10 700

Thus, preliminary results from our tutoring experiment and our analyses of Mr. Kent’s teaching are both consistent with our third explanation that, by positioning students as authors of their own learning and making connections with prior settings, expansive framing encourages students to bring in prior knowledge, including outside examples and 705 710

TABLE 2  
 Student Reports About How Often They Transfer-In Their Prior Knowledge

How Often During a Typical Biology Class Do YOU Think About or Use Ideas That You Already Knew From . . .	Never	Rarely	Sometimes	Often	All the Time
Within the previous few days?	0.0%	0.0%	27.3%	33.3%	39.4%
Within the previous few weeks?	0.0%	3.0%	39.4%	33.3%	24.2%
Within the last year?	0.0%	28.1%	43.8%	9.4%	18.8%
Longer than a year before?	16.1%	29.0%	35.5%	16.1%	3.2%

abstract generalizations, which previous research has shown increases students' propensity to transfer.

**EXPLANATION 4: AUTHORSHIP PROMOTES ACCOUNTABILITY TO PARTICULAR CONTENT**

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Positioning students as authors through the use of expansive framing may also promote accountability in ways that lead to transfer. If a student shares particular content knowledge, that student can be framed as the author of that content and be publicly recognized as such. The student then becomes expected to be able to use that content during transfer opportunities.

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For example, Engle (2006b; Engle & Conant, 2002) described a classroom where student groups were each assigned research projects about a particular endangered animal population. Within these groups, individual students were assigned particular topics about the populations for which they were to author oral explanations and written reports. The positioning of students as authors included language that attributed explanations about content to specific students or groups of students, rather than to the teacher or textbook (e.g., Teacher: You've [the student or student group has] just explained something to me [adapted from Engle, 2006b, p. 486]). Over time, these students became positioned as local experts about the content they had authored (Brown et al., 1993; Engle & Conant, 2002). Whenever anyone visited the classroom, each student-expert was expected to teach the visitor about their topic (Engle & Conant, 2002), which provided opportunities for students to transfer what they had learned. In later individual transfer assessments, Engle (2006a) found that students regularly referenced their own research as with one whale group student who explained why birthrate matters for species survival and endangerment by saying, "Like, that's like the whales. They only have like one calf every four out of five years. And by people hunting them, they can die off quickly" (p. 18). Thus, through authorship, students in this class were held accountable to the explanations they had previously authored and were able to transfer these explanations to new contexts.

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This example illustrates the proposal that students who are positioned as authors of particular content during learning are then held accountable for that content by others. As a result, this accountability increases the likelihood that students will transfer the particular content they authored in future contexts.

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**EXPLANATION 5: AUTHORSHIP AS A PRACTICE PROMOTES GENERATION AND ADAPTATION OF KNOWLEDGE IN TRANSFER CONTEXTS**

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Finally, expansive framing may allow students to author content regularly such that they eventually assume authorship as

a standard practice. This authorship role means that when students are faced with potentially new transfer problems they are ready to generate a response by adapting their existing knowledge. As compared to Explanation 4, we do not intend to suggest that students are being prepared to transfer specific content in specific transfer-related tasks. Rather, we are proposing that through regularly practicing authorship as a result of expansive framing, students begin to see themselves as being capable of addressing unfamiliar situations using what they already know just as authors do. In Mr. Kent's classroom, authorship of ideas became a regular practice. In the following example, we see a pair of his students adapting their prior knowledge and generating new knowledge while responding to a transfer problem in which they were asked to make connections between materials from three different units:

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insert comma

- 1 Edward: Meiosis is sex cells.
- 2 Adrienne: Meiosis is made [inaudible] protein synthesis?
- 3 Edward: Protein synthesis is how when DNA makes RNA? And RNA goes to the ribosomes 780
- 4 Adrienne: Okay.
- 5 Edward: And makes [inaudible].
- 6 Adrienne: That kinda links because- To make the- to make the zygote or whatever, DNA is (..) chromosomes from the parents, right? 785
- 7 Edward: (..) Wait, what? [laughs]
- 8 Adrienne: Hmm chromosomes from the parent, so it like produces protein. (..) It makes it, that makes the kid?
- 9 Edward: So you're saying protein synthesis makes a kid?
- 10 Adrienne: Yeah. 790
- 11 Edward: Makes the body?
- 12 Adrienne: Yeah, doesn't it?
- 13 Edward: So- so protein- how does protein synthesis links to genetic heredity?
- 14 Adrienne: Because DNA, 795
- 15 Edward: Well yeah.
- 16 Adrienne: that's what DNA is like, right? DNA is (..) the kid, you get the baby . . .
- 17 Edward: So (..) meiosis links to genetic heredity because of um the sex cells? 800
- 18 Adrienne: Yeah.
- 19 Edward: And then protein synthesis is for building the body?
- 20 Adrienne: Mmhmm. [in agreement]

In this example, we see this pair of students combine their knowledge and adapt their understandings of concepts that they learned from previous units to related concepts in the current unit. Edward brought in his knowledge about the Central Dogma of molecular biology from what he learned in the Protein Synthesis Unit by describing the process of DNA leading to protein synthesis (Turn 3). Adrienne then "linked" this idea to meiosis by connecting DNA to the formation of zygotes (Turn 6). The students then generated the idea that the chromosomes or DNA that are involved in the

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815 synthesis of proteins also produce proteins that “makes a kid”  
or “the body” (Turns 8–12). Next, they added genetic hered-  
ity to the conversation by connecting it to meiosis through  
the presence of DNA and sex cells (Turns 13–18). The stu-  
820 dents finally conclude that protein synthesis is what builds the  
body (Turns 19–20). Thus, in part because of the supported  
practice of authorship, Edward and Adrienne were able to  
approach a novel situation, in which they were asked to con-  
nect various topics learned at different times in the school  
825 year, by adapting their prior knowledge about several topics  
and generating connections between them and the units from  
which they were drawn.

Although the number of students examined is small, this  
example is consistent with our hypothesis that students who  
are regularly positioned as authors are likely to adopt author-  
830 ship as a practice. As a result, these students may become  
proficient at adapting their knowledge to fit novel situations  
or, in other words, to transfer appropriate knowledge in future  
contexts.

#### 835 POTENTIAL INTERACTIONS BETWEEN THE FIVE EXPLANATIONS

Although a detailed discussion of the interactions between  
these five explanations for how expansive framing promotes  
transfer requires further research, we have identified several  
ways that they could potentially interact. First, as shown in  
840 Figure 2, the two main aspects that make up expansive fram-  
ing group the explanations based on their origins in framing  
settings as connected or in promoting student authorship.  
Specifically, Explanations 1 and 2 derive from connecting  
settings whereas Explanations 4 and 5 derive from promot-  
845 ing student authorship. Explanation 3, in contrast, has its  
origins in both of these aspects of expansive framing.

Second, two of the explanations function by improving  
students’ learning, which then enhances transfer. Specifically,  
in Explanation 1, when a student expects that he or she will  
850 need to use what is being learned in connected settings, the  
student improves his or her learning process in preparation  
for transfer. Similarly, in Explanation 3, by transferring-in his  
or her prior knowledge during learning, the student improves  
his or her learning process.

855 A third connection that we identified reveals that three  
of the explanations depend on expansive framing occurring  
specifically in the learning context rather than in the transfer  
context. Students expecting that they will need to use what  
they learn later (Explanation 1), viewing their knowledge  
860 as both relevant and desired socially (Explanation 3), and  
adopting the practice of authoring knowledge (Explanation  
5), all require that the learning context be framed expansively.  
In contrast, when a student views what was learning before  
as relevant in a potential transfer context (Explanation 2), or  
865 when a student becomes publicly recognized as the author  
of particular transferable content (Explanation 4), it is not

essential that expansive framing occur when the content was  
actually learned.

870 Fourth, if students are frequently recognized in public as  
the author of content (Explanation 4), it is likely that the  
student will eventually adopt authorship as a general practice  
(Explanation 5).

875 Finally, several explanations may connect to one another  
over time. For example, a student may find her prior knowl-  
edge to have continued relevance in a particular social context  
(Explanation 2) in which someone requests that she explain  
her understanding of a topic. By responding to this request,  
it is likely that the student now begins to view her knowledge  
as socially desired (Explanation 3). Finally, the other person  
880 in the conversation may come to recognize her for the expla-  
nation she authored and from then on hold her accountable  
for the content she shared (Explanation 4).

insert commas before and after  
"from then on"

#### A RESEARCH AGENDA HOW FRAMING AFFECTS TRANSFER

885 In this article, we have gone beyond prior work that focuses  
on documenting that there is an effect of framing contexts  
on transfer to begin constructing several explanations of ex-  
actly *how* expansive framing may promote transfer. In so  
doing, we have been careful to consider how framing may  
890 work both independently of and in coordination with other  
known transfer mechanisms. We also recognize that these  
explanations may often work in concert and that there are  
undoubtedly complex relationships between them, some of  
which we have identified. Because of this, we now propose  
895 a research agenda for investigating each explanation and the  
relationships between them.

We suggest three kinds of studies that are likely to be  
especially fruitful: (a) experiments focused on disentangling  
the effects of different aspects of framing, (b) comparative  
900 studies in classroom settings, and (c) microgenetic investiga-  
tions that provide data-grounded explanations of how each  
set of processes unfolds, separately or in concert, to foster  
transfer.

#### Disentangling Experiments

905 Considering that current research suggests that expansive  
framing as a whole enhances transfer, a key next step is  
to manipulate the framing of different aspects of contexts  
separately and in coordination with one another in order to  
ascertain their individual and combined effects on transfer.  
910 In particular, given that three of the proposed explanations  
for how framing affects transfer are prompted by the framing  
of student roles as authors and three of the proposed explana-  
tions are prompted by framing settings (with Explanation 3  
being prompted by both), a clear next step is to run a 2 × 2 ex-  
915 perimental design in which student roles (expansive: author  
vs. bounded: spokesperson) are crossed with the framing of

change "learning" to  
"learned"

settings (expansive: linked vs. bounded: disconnected). This design will allow us to see which of these aspects of framing matter for which kinds of transfer and whether they each make independent contributions or if the whole is greater than the sum of the parts. Additional follow-up experiments can be run to further disentangle these effects.

A second kind of disentangling experiment that would be valuable would be one in which the timing of expansive framing is manipulated, with the effects on different kinds of transfer assessed.<sup>5</sup> As previously described, some of the proposed explanations rely on expansive framing during the learning process (Explanations 1, 3 and 5), whereas others would still be at least partially effective even if expansive framing is provided after learning (definitely Explanation 2 and perhaps also Explanation 4). Given that, manipulating when expansive framing occurs would allow us to further distinguish between these explanations.

As noted in Engle et al. (2011), such experiments “will simultaneously advance understanding of how exactly framing works, provide additional replication of the effects of framing on transfer, and guide educators about which aspects of framing to focus on” (p. 621).

### Comparative Classroom Studies

Another way to learn whether and how framing affects transfer is to make systematic comparisons between and within classroom-based case studies. To compare the effects between bounded and expansive framing, teachers teaching multiple sections of the same course can be encouraged to implement more bounded or more expansive framing in order to see what benefit, if any, the expansive implementation has on students’ propensity to demonstrate different kinds of transfer.

At the same time, within studies of particular classrooms in which expansive framing is employed, it is possible to see whether there are correlations between the degree to which each student transfers and the degree of each student’s awareness and uptake of expansive framing. Specifically, one could examine the degree to which different students appear to detect the existence of different aspects of the expansive framing and show evidence of “taking it up” (Austin, 1962; Clark, 1996) in their own behavior through a combination of surveys and interviews. This research then would allow one to see whether those students who noticed and responded to the expansive framing more strongly were also the same students who show greater evidence of transfer on assessments after controlling for other predictors of transfer.<sup>6</sup>

<sup>5</sup>We thank Rob Goldstone for this suggestion.

<sup>6</sup>Evidence of this sort is currently being generated (Meyer, 2012). Preliminary results of exploratory correlational and regression analyses (Engle, Meyer, & Chong, 2012) showed correlations between three different measures of transfer and students’ responsiveness to 10 different instances of expansive framing. One of the measures was tense consistency - change “show” to “showed”; or perhaps better, keep “show” and change “noticed and responded” to “notice and respond”

### Microgenetic Investigations

Finally, both kinds of studies can embed microgenetic investigations that are focused on directly observing the hypothesized processes in action (Maxwell, 2004a, 2004b; Saxe, 2002; Siegler Shadish, Cook & Campbell, 2002; 2006). Intensive videotaping combined with interviewing and documentation of student work and instructional materials during the complete span in which learning and transfer take place can allow one to develop explanations for cases in which expansive framing has been shown to relate to subsequent transfer, which would be documented not just with formal assessments but also by examining subsequent activity after instruction for evidence of students using what they had learned in their own ways (Lobato, 2012/this issue).

Such explanations would trace how an instructor’s framing was responded to by a student in ways that then affected their learning processes, the use of any known or hypothesized transfer mechanisms, and eventually how and what they were able to transfer. We have already begun this work by explaining the surprising transfer of one struggling student in another of Mr. Kent’s high school biology classes (Lam et al., 2012). The validity of such explanations can be further increased by also explaining contrasting cases in which transfer did not occur.

Interviews with students in which they are asked to explain how they themselves addressed transfer situations may also help inform which of the proposed processes were involved (Lobato, 2012/this issue). Such microgenetic investigations have the potential for further specifying how each process works for individual students, based on how they themselves interpret and respond to different framings (cf. Lobato, 2012/this issue; Lobato et al., 1999). It may also lead to potentially identifying other ways in which expansive framing promotes transfer. In addition, these investigations provide especially fertile ground for investigating how the five proposed explanations can interact with one another, in real time, and for particular students.

### CONCLUDING THOUGHTS 1000

By focusing on the effects of expansive framing on transfer, we are addressing an institutional problem that exists in much formal education, especially in high schools and beyond

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setting (time, place, and participants). Most correlations were positive and involved students reporting that they had adopted the framing in their actions rather than just agreed with it. Knowing the content to be transferred was correlated with two of the three measures of transfer while many potential predictors of learning like prior grades, test scores, motivational variables, and standard demographic variables did not correlate with transfer. The best regression models all involved expansive framing as predictors and were able to account for between 26% and 60% of the variance in transfer. However, these results are preliminary as we have not yet been able to include in our analyses useful measures of each student’s exposure to classical transfer mechanisms like generalizing and comparing examples.

1005 (Sizer, 1984), in which bounded framing has become the working norm. Students' classes are often framed as being completely separate from one another such that they are considered to involve completely different people, be about disconnected topics (cf. Richland et al., 2012/this issue), and happen in distinct places and times. Prior to the institution of schooling, learning may not have been as compartmentalized as in this age, and as a result, studies of transfer across contexts may have been moot because of the much broader way that learning was understood by both learners and teachers.

1010 Compared to other methods of fostering transfer, expansive framing is widely applicable to all academic subjects and adaptable to a variety of instructional methods. Standard content-based instructional methods for fostering transfer need to be precisely specified for that particular content, a very time-consuming process. In contrast, methods for expansively framing learning contexts can be implemented in similar ways, no matter what topic or discipline is being learned. In addition, the expansive framing of settings in particular can be used across all forms of instruction from traditional lectures to discovery-based approaches or any other variation or combination of these. All the instructor needs to do is connect the learning environment to other times, places, and participants in ways that his or her students will believe and be ready to act upon (Zheng, Meyer, & Engle, 2012). In effect, expansive framing allows instructors to better leverage whatever student learning they are able to achieve through whatever means.

1020 At the same time, however, we do not claim that expansive framing is the be-all or end-all for instruction. Our informal observations of tutoring and classroom instruction as well as broader theoretical considerations suggest that there may be costs as well as benefits of expansive framing for both learning and transfer. For example, we observed that a few learners in the expansive framing condition of the Engle et al., (2011) tutoring experiment had a tendency to bring in so much prior knowledge during learning that they became cognitively overwhelmed or had difficulty focusing on what the provided text and diagrams could contribute to their understanding. Thus, it may make sense for the beginnings and endings of lessons or curriculum units to be framed more expansively but to use a somewhat less expansive framing when students need to focus on learning important new material. In such circumstances, the advantage for learning in a more bounded framing is that it could help students to focus exclusively on the content at hand without being distracted by other knowledge.

1040 In addition, by itself expansive framing encourages learners to regularly use what they already know, but it does not provide resources for students to judge which prior knowledge is the most *appropriate* for a particular problem or issue. By itself, then, expansive framing can lead to over-generalization (Engle, 2006) or what is also called "negative transfer" (see also Schwartz et al., 2012/this issue). Therefore expansive framing should be regularly paired with activities

in which learners critically evaluate the knowledge they have transferred in for its relevance and validity. Some of the 1060 techniques that Schwartz et al. (2012/this issue) suggest for avoiding negative transfer like proactively seeking feedback are likely to be particularly helpful in this regard.

For this reason, it also may make sense for instruction to employ more targeted expansive framings in which students 1065 are provided with specific contexts for when generalization from the learned content will be most appropriate, such as specifying that a particular topic will be relevant both in a future Chemistry class and for helping themselves or loved ones address a common disease. This targeted expansive 1070 framing contrasts with a more general expansive framing where only vague contexts are provided and thus expands to include all contexts, such as telling students that what they are learning will be useful "in the future" or "almost everywhere." A targeted expansive framing may reduce 1075 negative transfer that occurs when irrelevant content is transferred, or is transferred inappropriately. However, it is possible that only using targeted expansive framing may constrain scientific discovery, which often involves creating deep analogies across contexts that were not initially thought 1080 to be relevant to one another (e.g., Goldstone & Wilensky, 2008). In this case, an expansive framing that encompasses all contexts may be more effective.<sup>7</sup>

Nonetheless, it has long been recognized that the key challenge to transfer is in students being reminded of and 1085 actually bringing in their knowledge in the first place (e.g., Loewenstein, 2010; Reeves & Weisberg, 1994; Ross, 1984). It is in addressing this key challenge that expansive framing is particularly powerful.

In closing, we hope this article will advance future inves- 1090 tigation of the relationships between framing and transfer. We believe it provides a basis for researchers to be able to provide clear demonstrations of the multiple ways in which framing affects transfer and how they interact with each other in real learning situations. 1095

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<sup>7</sup>Perhaps a way to get the best of both extremes would be to specify a few key transfer contexts for the knowledge being learned and then specifically open up the possibility of additional contexts with phrases like "and beyond" or "and more." If done in a believable way, this phrasing may also prompt students to think about additional contexts in which they can use what they are learning.

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# The Actor-Oriented Transfer Perspective and Its Contributions to Educational Research and Practice

Joanne Lobato

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## The Actor-Oriented Transfer Perspective and Its Contributions to Educational Research and Practice

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Although any mainstream thought is subject to theoretical challenges, the challenges to the mainstream cognitive perspective on transfer have had an unfortunate divisive effect. This article takes a pragmatic view that transfer perspectives are simply *designed objects* (Plomp & Nieveen, 2007), which provide different information for different purposes. Specifically, this paper compares one alternative approach—the *actor-oriented transfer perspective*—with the mainstream cognitive perspective on transfer, by examining the points of compatibility and tension across 5 dimensions. As a result, a space is opened up to explore 3 issues that are particularly well suited to an actor-oriented transfer approach: (a) how students interpret transfer situations, (b) the socially situated nature of transfer processes in classrooms, and (c) how contextual-sensitivity can play a productive role in the transfer of learning. Exploring the benefits and trade-offs of various approaches allows for greater understanding of the contributions of each perspective to educational research and practice.

People often notice the transfer of learning when it *doesn't* happen. For example, a mother is disappointed when her 3-year-old son fails to use his enumeration skills to count out the number of placemats she lays on the table. A calculus professor wonders how to help his college students when they are unable to solve a straightforward physics application using skills of integration they already have. A high school mathematics teacher is disheartened when students who had performed well on a test of linear functions and slope respond to a novel task by treating slope as a difference rather than a ratio. Our expectation for transfer in each case may be an indication of our everyday experience of the world having order and regularity: Past experiences carry over from one context to the next. Furthermore, nearly all learning theories presume that prior knowledge influences the comprehension of any new situation (Anderson, 1996; Bereiter, 1995; Booker, 1996; Bransford & McCarrell, 1974; Hatano & Greeno, 1999). For example, according to Dewey's (1938) principle of the continuity of experience, "Every experience both takes up something from those which have

gone before and modifies in some way the quality of those which come after" (p. 34).

On the other hand, transfer has been notoriously illusive to produce consistently in laboratory studies (Barnett & Ceci, 2002; Detterman, 1993; Perkins & Salomon, 1989). Furthermore, there have been numerous critiques of the theoretical and methodological underpinnings of transfer research (Beach, 1999, 2003; Bransford & Schwartz, 1999; Evans, 1998; Greeno, 1997; Gruber, Law, Mandl, & Renkl, 1996; Lave, 1988; Packer, 2001; Tuomi-Gröhn & Engeström, 2003). As a result, some researchers have abandoned transfer as a research construct (Carragher & Schliemann, 2002; Hammer, Elby, Scherr, & Redish, 2005; Laboratory of Comparative Human Cognition [LCHC], 1983), whereas others have developed alternative transfer perspectives (Beach, 1999, 2003; Bransford & Schwartz, 1999; Greeno, Smith, & Moore, 1993; Nemirovsky, 2011; Tuomi-Gröhn & Engeström, 2003; Wagner, 2006, 2010). This article focuses on one such alternative approach—the *actor-oriented transfer perspective* (AOT; Lobato, 2003, 2006, 2008a, 2008b). Among other points, I argue that AOT can be used as a lens to detect instances of the generalization of learning experiences (meaning the expansion of instructional or everyday experiences beyond the conditions of initial learning), even when there is a lack of transfer according to traditional definitions, as is the case in the three opening scenarios.

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65 The AOT perspective emerged in response to critiques of  
 the mainstream cognitive approach to transfer, which often  
 challenged its epistemological assumptions. However, I take  
 a more pragmatic view that models of transfer are simply  
*designed objects* (Plomp & Nieveen, 2007), which provide  
 70 different information for different purposes. Rather than con-  
 ceiving of a particular perspective as being flawed and in need  
 of replacement, points of compatibility and tension between  
 models of transfer are explored, thus allowing for greater un-  
 derstanding of the contributions to educational research and  
 75 practice by each perspective. Specifically, I begin by examin-  
 ing the benefits and trade-offs of both mainstream cognitive  
 and actor-oriented perspectives on the transfer of learning,  
 with the goal of fleshing out the tenets of AOT and open-  
 ing up a space to explore transfer issues that are particularly  
 80 well suited to an AOT approach. After all, there is no point  
 in presenting an alternative approach if the dominant per-  
 spective can be used to satisfactorily explore the broad array  
 of phenomena that interest transfer researchers. The goal of  
 this article is not to supplant one perspective but rather to  
 85 articulate specific issues that can benefit from an alternative  
 approach. To that end, I draw upon empirical studies from  
 a variety of researchers operating from an AOT perspective  
 to articulate some specific ways in which AOT can afford  
 new insights into understanding: (a) how students interpret  
 90 transfer situations, (b) the socially situated nature of transfer  
 processes in classrooms, and (c) how contextual-sensitivity  
 can play a productive role in the transfer of learning.

95 DIFFERENTIATING BETWEEN  
 THE MAINSTREAM COGNITIVE  
 AND ACTOR-ORIENTED PERSPECTIVES  
 ON TRANSFER: POINTS OF COMPATIBILITY  
 AND TENSION

Mainstream Cognitive Perspective on Transfer

100 By the mainstream cognitive perspective on transfer, I refer  
 broadly to the family of approaches that emerged during the  
 last half of the 20th century as part of the cognitive revolution  
 (offered by a variety of researchers including but not limited  
 to Bassok & Holyoak, 1993; Gentner, 1983, 1989; Nokes,  
 2009; Novick, 1988; Reed, 1993; Ross, 1984; Singley &  
 105 Anderson, 1989; Sternberg & Frensch, 1993). Researchers  
 formulated explanations for transfer based on relationships  
 between a learner's mental representations, as opposed to  
 the theories posited by associationists and behaviorists based  
 on environmental similarity and observable stimuli (Royer,  
 110 Mestre, & Dufresne, 2005). A hallmark of this general ap-  
 proach is a commitment to a cognitive architecture com-  
 prising (a) short-term, long-term, and sensory memories; (b)  
 representations as symbolic mental symbol structures that  
 encode, process, and store one's experiences; and (c) a con-

115 trol mechanism to oversee the retrieval and utilization of  
 information (Bruer, 2001; Ericsson & Simon, 1993).

Under this general umbrella exist different strands of re-  
 search. One prominent approach is the cognitive descendent  
 to Thorndike's (1906) theory of identical elements. In their  
 seminal cognitive account of transfer, Singley and Anderson 120  
 (1989) explained that they "resurrected Thorndike's theory  
 by redefining his identical elements as the units of declar-  
 ative and procedural knowledge" (p. 248), thus addressing  
 Thorndike's lack of an explicit representational language,  
 125 which can allow for the flexible reconstruction of knowl-  
 edge. A second influential theory is the structure-mapping  
 approach of Gentner and colleagues, developed as an ac-  
 count of analogical reasoning but readily adapted to exam-  
 ine lateral transfer (Gentner, 1983, 1989; Gentner & Kurtz,  
 2006; Gentner, Loewenstein, & Thompson, 2003; Gentner & 130  
 Markman, 1997). From this perspective, transfer involves a  
 mapping between mental representations of relations among  
 objects and their attributes in initial learning and transfer  
 situations. Other points of diversity within the mainstream  
 cognitive approach include (a) the use of different subpro- 135  
 cesses to explain the occurrence of transfer, such as constraint  
 violation (Ohlsson & Rees, 1991) or analogical systematicity  
 (Markman & Gentner, 2000); (b) a focus on different types  
 of transfer (as summarized in Barnett & Ceci, 2002), and (c) 140  
 disagreements regarding whether the mental representation  
 of a transfer situation is constructed during engagement with  
 that situation (e.g., Gentner, 1983) or in the initial learning  
 situation (Gick & Holyoak, 1983).

145 Despite these differences, there are many common  
 features among family members of the mainstream cognitive  
 perspective on transfer. First, the formation of sufficiently  
 abstract representations is a necessary condition for transfer  
 (so that properties and relations can be recognized in  
 both initial and transfer situations), where abstraction is  
 conceived as a process of decontextualization (Fuchs et al., 150  
 2003; Gentner, 1983; Reeves & Weisberg, 1994; Singley &  
 Anderson, 1989). Second, explanations for the occurrence  
 of transfer are based on the psychological invariance of  
 symbolic mental representations (Bassok & Holyoak, 1993;  
 Nokes, 2009; Sternberg & Frensch, 1993). Finally, transfer 155  
 occurs if the representations that people construct of initial  
 learning and transfer situations are identical, overlap, or can  
 be related via mapping (Anderson, Corbett, Koedinger, &  
 Pelletier, 1995; Gentner et al., 2003; Gick & Holyoak, 1983,  
 1987; Novick, 1988; Reed, 1993). 160

From a mainstream cognitive perspective, transfer is char-  
 acterized as "how knowledge acquired from one task or sit-  
 uation can be applied to a different one" (Nokes, 2009, p.  
 2). From the AOT perspective, transfer is defined as the gen-  
 165 eralization of learning, which also can be understood as the  
 influence of a learner's prior activities on her activity in novel  
 situations (Lobato, 2008a). The differences between perspec-  
 tives may not be apparent from these definitions, especially  
 because there are instances in which researchers operating

170 from the mainstream cognitive perspective have described transfer as the influence of prior learning experiences on attempts to solve problems in new situations (see Marini & Genereux, 1995; Reed, Ernst, & Banerji, 1974). Thus, I explore five dimensions across which the two perspectives differ: (a) the nature of knowing and representing, (b) point of view, (c) what transfers, (d) methods, and (e) goals. For each dimension, I discuss points of contact and tensions as well as the benefits and trade-offs of each perspective.

### Nature of Knowing and Representing

180 Both actor-oriented and mainstream cognitive perspectives on transfer share the view that the basis for transfer is psychological similarity rather than similar features of physical or task environments (à la Thorndike, 1906). However, the AOT perspective places greater emphasis on the interpretative nature of knowing than is present in many studies conducted from a mainstream cognitive perspective. This means that researchers operating from an AOT perspective look for the ways in which students appear to treat transfer situations as instances of something they have already thought about, based on their interpretation and construal of meaning of the activities and events in the initial learning situation. That is, knowing and representing arise as a product of interpretive engagement with the experiential world, through an interaction of prior learning experiences, task and artifactual affordances, discursive interplay with others, and personal goals.

190 Within the mainstream cognitive perspective on transfer, there appears to be a much closer correspondence between events/objects in the world and mental representations. In principle this relationship is problematized, as evidenced in the following quote from Anderson, Reder, and Simon (2000): “The representational view of mind, as practiced in cognitive psychology, certainly makes no claims that the mind represents the world accurately or completely” (p. 14). Similarly, Gentner and Markman (1997) acknowledged that mental representations are informed by an individual’s goals and prior knowledge. However, after analyzing many empirical studies conducted within both the identical elements and structure-mapping strands, Wagner (2010) concluded that in practicality both models tend to treat representations as unproblematic, “as if situational structure could be directly perceived in the world” (p. 447). This stance is also reflected in other empirical and theoretical papers, for example, by English and Halford (1995), when they stated that “cognitive processes entail operations on mental representations, which are internal mental structures that correspond to the structure of a segment of the world” (p. 21); by Rittle-Johnson, Siegler, and Alibali (2001), when they code mental presentations of learning and transfer situations as either correct or incorrect; and by Anderson (1996), when he claimed that “declarative knowledge is a fairly direct encoding of things in our environment; procedural knowledge is a fairly direct encoding of observed transformations” (p. 364). A notable

exception is the work by Day and Goldstone (2011), who attempted to disambiguate external similarity from similar mental representations. 225

These observations are not intended as criticism; rather, the differences between perspectives suggest implications regarding optimal research domains for each perspective. For example, the research venues that can most benefit from the use of an AOT perspective are ones with semantically rich content that is open to a variety of often idiosyncratic ways of comprehending and interpreting. The AOT approach was not developed to address areas that have typically been the focus of research from the mainstream cognitive perspective, such as the transfer of procedural skill (e.g., transfer across text editors, Singley & Anderson, 1989; transfer of LOGO debugging skills, Klahr & Carver, 1988), puzzle-type problems (e.g., Tower of Hanoi/Monster problems, Kotovsky & Fallside, 1989), procedural elements of semantically rich domains (e.g., algebraic skills in word problems, Koedinger & Anderson, 1998), and tasks with a rule-oriented or syntactic focus (e.g., continuing sequences of letters in a pattern, Nokes, 2009). 230 235 240 245

To illustrate what is meant by focusing on the interpretative nature of knowing within a transfer study, I briefly turn to an example from my previous research with colleagues (Lobato, Ellis, & Muñoz, 2003). The study occurred in the ninth-grade algebra classroom of a teacher using a reform-oriented curricular unit on linear functions. We expected that the development of linear functions as dependency relationships in multiple real-world situations would increase the likelihood that students would successfully negotiate the quantitative complexity of novel transfer situations. Furthermore, the unit spent much longer investigating slope than is typical in traditional algebra classrooms, and it linked informal explorations with the presentation of the slope formula ( $m = \frac{y_2 - y_1}{x_2 - x_1}$ ). Thus, we were surprised when qualitative analysis revealed that the interview participants interpreted the slope of a linear function, not as a *ratio* of the changes in the dependent variable for each 1-unit change in the corresponding independent variable, but incorrectly as a *difference* (in *y*-values, *x*-values, or in the scale of the *x*-axis). For example, in an interview task in which the slope represented the ratio of the amount of water collected from a leaking faucet over time (i.e., 8 oz per hour), a common response was to identify the difference in amounts of water presented in a table of data, without regard for the corresponding difference in time (e.g., using 10 as the slope when 10 oz of water leaked in 1.25 hr rather than 1 hr). We found this surprising because these students had been selected as higher performers in the class and had been able to correctly find the slope of linear functions in unit quizzes prepared by their teacher. Perhaps their understanding was bound to the context of the learning situation. 250 255 260 265 270

However, closer examination revealed that all of the students who produced an equation for a given line or table wrote “ $y = \square \pm \square x$ ” (rather than the more standard  $y = mx + b$ ) and referred to the two boxes respectively as the 275

“starting point” and “what it goes up by.” The fact that this language and these inscriptions were used in class suggested that students were *generalizing* or expanding their instructional experiences beyond the conditions of initial learning. This was confirmed during qualitative analysis of videotaped classroom episodes. Specifically, we identified several features of the classroom practices that regularly directed students’ attention to various differences in a single quantity rather than to the coordination of quantities. In each case, the classroom practices were understandable, despite the unforeseen and undesirable consequences. For example, the teacher regularly used the phrase “goes up by” when talking about slope, perhaps in an effort to connect with students through initial use of more accessible language before moving to formal symbolization. Although the teacher used the phrase to speak about ratios (e.g., “the *y*’s go up by 3 when the *x*’s go up by 1”), the students apparently interpreted the teacher’s utterances in terms of differences in a single quantity. In sum, this example demonstrates the unexpected connections that learners can make between their personal interpretations of learning experiences and transfer situations.

A critical reader may question the value of identifying generalizing activity that results in incorrect performance. However, the AOT perspective responds to the following challenge by Bransford and Schwarz (1999):

Prevailing theories and methods of measuring transfer work well for studying full-blown expertise, but they represent too blunt an instrument for studying the smaller changes in learning that lead to the development of expertise. New theories and measures of transfer are required. (p. 24)

Novices are likely to demonstrate greater variety in their interpretations of learning environments than experts; thus, making them a desirable object of research from the AOT perspective. Furthermore, I revisit this study later to demonstrate how information from an AOT study can inform revisions to curriculum and pedagogy during iterative cycles of instructional design, leading to improvements in the nature of what is learned and transferred.

**Point of View**

Central to the AOT perspective is the distinction between an “actor’s” and an “observer’s” point of view. Taking an observer’s point of view entails predetermining the particular strategy, principle, or heuristic that learners need to demonstrate in order for their work on a novel task to count as transfer. It is also in operation when learners perform correctly on tasks that an observer sees as structurally similar to initial learning tasks, and inferences are made that the learner sees the same similarity as the observer. When taking an actor’s point of view, the researcher does not measure transfer against a particular cognitive or behavioral target but rather investigates instances in which the students’ prior experiences shaped their activity in the transfer situation, even if the result is non-normative or incorrect performance.

Transfer research from the mainstream cognitive perspective is typically conducted from an observer’s point of view. Consider the study by Bassok and Holyoak (1989) examining analogical transfer across the domains of algebra and physics. In one of the experiments, half of the ninth-grade students were taught formulas for arithmetic progression methods with practice on a variety of algebraic word problems, such as  $a_n = a_1 + (n - 1)d$ , where  $a_1$  and  $a_n$  are the initial and  $n$ th terms in the sequence, respectively, and  $d$  is the constant difference of successive terms. Similarly, the other half were taught formulas related to constant acceleration with practice on physics problems (i.e.,  $v_f = v_i + at$ , where  $v_i$  and  $v_f$  are the initial and final velocities of an object traveling in a straight line,  $a$  the constant acceleration, and  $t$  the time taken to move from the initial to the final state). Students were then asked to solve transfer tasks (such as those shown in Figure 1) from the domain in which they had not received instruction.

The measure of transfer was “whether the learned method had been applied to structurally isomorphic but unfamiliar problems” (p. 157), meaning that transfer was dependent on explicit evidence of the formula and notation taught in class. Using this standard, the algebra students successfully mapped the arithmetic-progression methods onto the physics problems 72% of the time. Additional verbal

Algebra	Physics
During a laboratory observation period it is found that the diameter of a tree increases the same amount each month. If the diameter was 8 mm at the beginning of the first month, and 56 mm at the end of the 24 <sup>th</sup> month, by how much does the diameter increase each month?	What is the acceleration (= increase in speed each second) of a racing car if its speed increased uniformly from 44 meters per second (44 m/s) at the beginning of the first second, to 55 m/s at the end of the 11 <sup>th</sup> second?

FIGURE 1 Representative matched pair of algebra and physics transfer items. From “Interdomain Transfer Between Isomorphic Topics in Algebra and Physics” by M. Bassok & K. J. Holyoak, 1989, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15.

protocol evidence supported the claim that the algebra students spontaneously recognized that the kinematics problems could be addressed using the arithmetic-progression formulas. In contrast, the physics students used the constant acceleration formulas on only 10% of the algebra problems. The researchers concluded that arithmetic-progression procedures transferred better than the kinematics procedures, due to the greater content specificity of the physics representations.

One benefit of the observer's point of view is the emergence of a yardstick to illuminate differences in reasoning. In this study, it helped distinguish the effect of training differences in learners' ability to map equations across domains. The observer's point of view can also be used effectively in the summative assessment of an instructional treatment. A trade-off is that the generalization of learning can be underestimated. For example, the physics students in the Bassok and Holyoak (1989) study did, in fact, solve 94% of algebra transfer tasks correctly (despite using the taught equations and notations on only 10% of the tasks). Their use of the same methods to solve both the algebra transfer tasks and the pretest items suggests that they were generalizing but that they generalized some experiences gained prior to the study rather than generalizing their experiences with the targeted techniques. A second trade-off is that dimensions related to learners' comprehension of situations can be overlooked as the basis for task isomorphism. Although the tasks in Figure 1 are isomorphic along the dimension of mapping values of terms in the same positions in two sequences, they are not isomorphic along the dimension of measurable attributes to be conceived. Using the physics formula to solve the tree diagram task entails mapping an *extensive quantity* (a directly measurable quantity—the tree diameter) onto a *first order ratio* (the ratio of two extensive quantities, here, the ratio of distance to time, or velocity) and a *first order ratio* (the growth rate of diameter) onto a *second order ratio* (the ratio of a ratio to an extensive quantity, here the ratio of velocity to time, or acceleration; J. L. Schwartz, 1988). Thus, according to the dimension of measurable attributes, the tree problem is isomorphic to a constant velocity rather than a constant acceleration problem. Research suggests that forming these different relationships among measurable attributes of a situation is a central yet challenging aspect of understanding this domain for novices (Lobato, Hohensee, Rhodehamel, & Diamond, in press; Stroup, 2002; Thompson, 1994).

The definition of transfer from an AOT perspective as the generalization of learning signifies a research interest in the expansion of experiences beyond the conditions of initial learning, rather than the formation of particular highly valued generalizations alone. Both represent legitimate but somewhat different avenues of research. To further illustrate the differences, consider a brief example of data analyzed from both observer and actor points of view. The data were collected from exams given to 139 high school introductory

algebra students participating in a 6-week unit on slope and linear functions (Lobato, 1996). The students performed well on tasks encountered in the experimental curriculum, such as finding the slope of staircases (87% correct) and lines (80% correct). The transfer tasks asked students to find the slope of a playground slide and the roof of a house. In each case, the slope can be determined by identifying and then measuring the "rise" or vertical change of the object (by fitting a staircase or stairstep to the object—a method taught in class), identifying and measuring the "run" or horizontal change of the object, and then dividing the rise by the run. Strong transfer findings were predicted, in part because the situation aligned with Singley and Anderson's (1989) finding of nearly total transfer for related-rates calculus problems given the conditions that the tasks shared the same production rules and solution methods and the students had extensive practice. Contrary to expectations, transfer was poor—40% to the slide task and 33% to the roof task.

Follow-up interviews using an AOT perspective presented a different picture, namely, that all interview participants demonstrated evidence of the generalization of their learning experiences. While working on the playground slide task (see Figure 2a), the students correctly recalled the slope formula as "rise divided by run" and treated the slope formula as relevant in the novel situation. However, they made incorrect rise and run choices. Jarek's response is particularly striking because the rise and run seem disconnected from the part of the apparatus that is steep (see Figure 2b). However, his interpretation of experiences with staircases during instruction was conceptually related to his reasoning on the transfer task. Specifically he appeared to look for a stair step in the slide setting (e.g., an object with connected "up" and "over" components that visually affords climbing in an imagined state of affairs), which he found on the right side of the slide (Figure 2c). The platform as the run may have held appeal because it was the only visible "tread" or "over" affordance. In sum, taking an actor's point of view helped illuminate ways in which learners' unanticipated interpretations of instructional experiences were connected to their comprehension of transfer situations. Furthermore, it helped identify elements of mathematical understanding (e.g., the constraint that mathematical "staircases" need to be connected to the part of the object that is steep), which can remain implicit in an expert model until their absence is surprisingly demonstrated in student work.

By revealing unexpected ways in which people generalize their learning experiences, the use of an actor's point of view can help guard against conclusions that reasoning is hopelessly context-bound or that transfer failures "are an inevitable consequence of the limited power and generality of human knowledge" (Singley & Anderson, 1989, p. 2; see also Detterman, 1993; Hatano, 1996; Perkins & Salomon, 1989). One trade-off of the AOT perspective is the time-intensive nature of the qualitative data analysis (especially because *what* is transferring is typically not known in

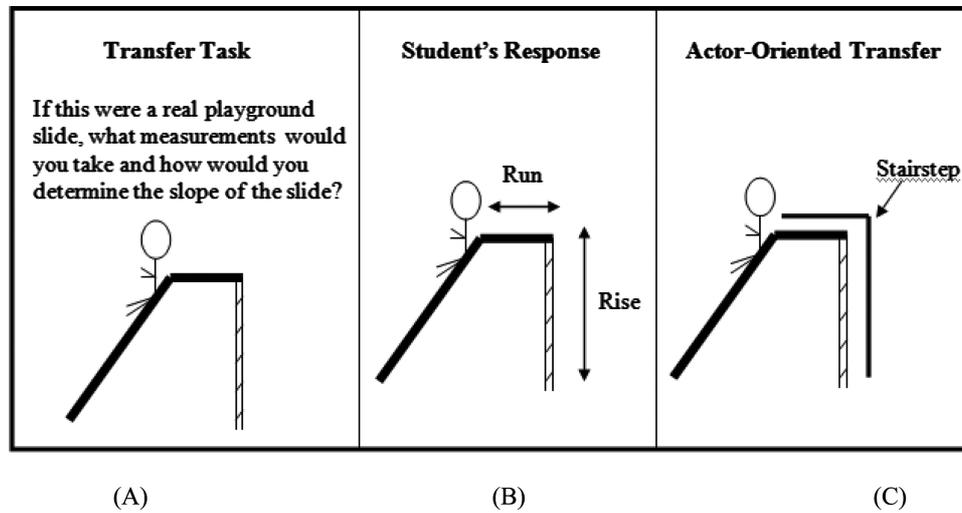


FIGURE 2 From Lobato's (1996) study: (a) the Transfer Task, (b) one student's response, which identified the  $\text{slope} = \text{rise}/\text{run}$  as the height of the ladder and the  $\text{run}$  as the length of the platform, and (c) possible image connecting transfer and learning tasks from the student's point of view.

advance) and the need of a research design that affords access to the influencing experience. Furthermore, a critical reader may interpret the slope study as simply juxtaposing novice with expert representations, which has been addressed from a mainstream cognitive perspective. For example, Novick (1988) found that when training and transfer tasks shared structural features but not surface features, experts were more likely to use the training-taught procedure to solve the transfer problems than novices were. On the other hand, when the two problems shared surface but not structural features, novices were more likely to continue using the taught procedure inappropriately (resulting in negative transfer). By similarly adopting an observer's perspective to interpret the results of the slope study, one can conclude that the students used a taught procedure ( $\text{slope} = \text{rise}/\text{run}$ ) inappropriately. However, this leaves unexplored the issue that the students' interpretation of the instruction did not match what was intended. Thus, the actor's point of view allows an investigation of the particular ways in which students interpret the meaning of slope, staircases, steepness, and so on. This opens up the issue of *what* transfers—a strategy versus one's comprehension of a situation—which I address next.

### What Transfers?

In their review of transfer research during the 20th century, Singley and Anderson (1989) concluded that there is little evidence for the transfer of general problem-solving faculties across a broad range of domains. Instead, much of the recent research from both mainstream cognitive and AOT perspectives has focused on the transfer of specific content knowledge. However, there is one important distinction between the nature of knowledge studied in mainstream cognitive accounts (particularly the common elements approach)

and AOT, namely, the transfer of well-defined actions and strategies versus a more holistic conceptualization. This distinction is elaborated through the following example.

Thompson (in press) interpreted a case study from his own research (Thompson, 1994) from both mainstream cognitive and AOT perspectives. The study began with a sixth-grader called JJ answering questions such as the following, "How much time will it take Turtle (a computer character) to travel 200 cm if he goes 25 cm/sec?" JJ drew successive line segments, each representing 25 cm, until she reached a total of 200 cm and then counted the number of segments—in this case, 8—for an answer of 8 s. She could also answer these questions using division (e.g., with  $200 \div 25$ ). JJ was then asked questions such as the following, "At what speed must Rabbit (a second computer character) travel so that it will travel 200 cm in 7 sec?" She initially experienced a dilemma because she wanted to make a speed segment but didn't know the length of the segment to draw. Consequently, she adopted a guess-and-test strategy, trying first one "speed" and then another, without the use of division.

According to Thompson, this episode would unlikely be considered an instance of transfer from the cognitive common elements perspective. When transfer involves comparing two productions (condition-action pairs) for different tasks, then the individual performs some well-defined mental or physical operation (often a strategy or calculation in a mathematical context), when the task representation meets particular conditions (Anderson, 1996, 2005; Anderson et al., 1995; Muldner & Conati, 2010; Singley & Anderson, 1989). Thus, Thompson concluded that JJ's work on the second type of task would not count as transfer under this perspective because the student did not use the same solution method.

However, Thompson claimed that this would count as complete transfer from an AOT perspective, where what

transferred was JJ's conceptualization of speed, distance, and time, rather than the reuse of a well-defined action. Specifically, speed was not a ratio for JJ but rather a distance (or what Thompson calls a "speed-length"). She comprehended both settings as essentially the same—that of traveling a distance in successive speed-lengths. In the first case, JJ imagined measuring the given distance in units of a speed-length, and the number of speed-lengths contained in the given distance told her the amount of time the character traveled. In the second situation, she again imagined measuring the given distance in units of a speed-length—this time a guessed speed-length guided by an estimate of how many speed-lengths it would take to create the given number of seconds. In a sense, she was searching for a ruler of the right length by which to measure the to-be-traveled distance. Thus, JJ appeared to comprehend the second situation as being pretty much the same as another that she had already thought about.

A benefit of targeting well-defined actions is that they translate well into the if/then statements of computer programs, which can then be used to build intelligent tutoring systems. The trade-off is that such an approach may not account for an underlying conceptualization that can give rise to multiple strategies or behavioral actions. That said, a reader may wonder, as Reed (in press) did, if the notion of mapping—the formulation of a set of systematic correspondences—could be used to establish commonalities between mainstream cognitive and AOT perspectives. For example, Reed interpreted the slope example with Jarek (from Figure 2) as an instance of a partial mapping (meaning partially successful because the rise but not the run component was correct) from the symbolic representation of the slope formula to the diagrammatic representation of the playground slide. In contrast, from an AOT perspective, I consider Jarek's work—much like JJ's—to indicate complete transfer of his conceptualization of slope. Jarek appeared to comprehend slope situations as linked with staircases, which in turn, brought to mind images of steps, with up and over components that afford climbing.

How one diagnoses the problem—as related to discrete actions, partial mappings, or an underlying conceptualization—has important implications for instructional responses. For example, Reed diagnosed Jarek's problem as failing to construct the auxiliary line segment that would allow a correct mapping to the run component. In response a teacher could present worked examples that include the critical parts of a diagram before asking students to construct them. From an AOT perspective, Jarek's conceptualization was problematic. He and the other students appeared to conceive of slope as two whole numbers—a rise and run value—which were not compared multiplicatively to form a ratio. Furthermore, Jarek's rise choice was correct only in a calculational sense, not a conceptual one, because it was disconnected from the part of the apparatus that was steep. Our subsequent design-based instructional approach focused on isolating the attribute to be measured and constructing slope as a ratio to measure

the particular attribute (Lobato & Siebert, 2002; Lobato & Thanheiser, 2000; Olive & Lobato, 2008).

## Methods

Singley and Anderson (1989) described the methods often used to establish transfer in both historical and mainstream cognitive approaches. Specifically, subjects are typically taught a solution, response, or principle in an initial learning situation and then solve a transfer task(s). The initial learning and transfer tasks share some structural features (e.g., a common solution approach) but have different surface forms (e.g., different word problem contexts or domain-specific details). The performance of the experimental group is compared with that of a control group, which is given the transfer tasks but receives no practice on the learning tasks. If the performance of the experimental group on the transfer tasks is better than the control group, then transfer is said to occur.

Some researchers have made adaptations to this basic approach by using multiple measures to capture the transfer of learning. For example, Chen and Klahr (1999) investigated the transfer of a "control of variables" strategy to design unconfounded experiments by using transfer tasks set in two contexts, a "strategy similarity awareness" measure, and a delayed remote transfer measure. Other studies have used verbal protocol methods to examine solution procedures (e.g., Bassok & Holyoak, 1989; Gentner, 1989; Nokes, 2009), though, according to Novick (1988), most transfer studies from a mainstream cognitive perspective rely primarily on performance measures. In addition, accounts of transfer found in ACT-R studies (Anderson, 1996, 2005; Koedinger & Terao, 2002; Singley & Anderson, 1989), demonstrate a care for "what" transfers in their articulation of fine-grained production rules (though in practicality, accuracy of performance or time to complete a task is often used, and the object of transfer is inferred). However, the use of a predetermined standard or a cognitive model based on an observer's perspective leaves an opening for more information to be gathered regarding unexpected ways in which people may construe learning and transfer situations as connected.

To provide this type of information, the AOT perspective relies on qualitative methods to identify the nature of students' reasoning in transfer situations and their comprehension of previous learning activities, allowing researchers to identify what transfers from an actor's point of view (Lobato, 2008a). Often inductive codes emerging from the data are used rather than a priori codes (Miles & Huberman, 1994), because the nature of reasoning in the transfer situation and the particular meanings students develop during instruction are often unanticipated. A typical AOT design (e.g., as used in Karakok, 2009, or Lobato & Siebert, 2002) relies on extended, conceptually oriented classroom instruction, followed by the use of transfer tasks in clinical interviews (Ginsburg, 1997), but one could use a series of interviews or examine the use of novel tasks during instruction (e.g., as illustrated by Ellis, 2007, and Sinha et al.,

2010). Within a classroom/interview design, conducting preinstructional interviews or relying on instructional settings where participants have limited knowledge of the content to be learned can help isolate the experience that is influencing participants' reasoning on the transfer tasks. Typically the interview data are analyzed using open coding from grounded theory (Strauss & Corbin, 1990) to categorize students' inferred ways of thinking, comprehending, and meaning-making related to the transfer tasks. The classroom data are then analyzed qualitatively to identify any plausible conceptual connections between the students' reasoning on the transfer tasks and the instructional activities.

There are benefits, as well as trade-offs, associated with the methodological approach of each transfer perspective. Specifically, the reliance on transfer as a performance measure allows researchers from a mainstream cognitive perspective to investigate the relationship between transfer and other factors such as motivation, achievement goals, metacognition, and learning disabilities (Belenky & Nokes-Malach, in press; Brownell, Mellard, & Deshler, 1993; Butterfield & Nelson, 1991; Pugh & Bergin, 2006). On the other hand, performance alone is a limited basis on which to infer an underlying cognitive model, as multiple models can lead to the same performance. This can be offset when qualitative methods are used, but the additional use of the observer's point of view can constrain the generalizing that is captured. On the other hand, the reliance on ethnographic methods constrains researchers to small sample sizes and brings with it the associated difficulties in generalizing claims and accounting for selection bias (Sloane & Gorard, 2003). However, a benefit associated with this trade-off is the ability of AOT methods to capture the often unexpected nature of reasoning on transfer tasks, interpretative meanings of learning activities, and personal connections constructed between learning and transfer situations.

When mainstream cognitive transfer studies are grounded in an experimental design, they can capitalize on the logic of stochastic causality to make claims about the effectiveness of both preparatory and learning activities on students' ability to perform on transfer tasks. This type of information may be of greater use to policymakers than the results from AOT approaches regarding the particular nature and quality of individuals' reasoning. In contrast, AOT studies are typically supported by Maxwell's (2004) articulation of a type of scientific explanation that identifies processes that connect events conceptually and that can help explain later events, qualitatively. This approach helps capture explanatory accounts of reasoning over extended periods of time, which can be useful in addressing questions of *how* or *why* something is happening.

## Goals

A major goal of mainstream cognitive transfer research is to document the occurrence of transfer (or explain the

failure of transfer), which includes investigating the types of knowledge that transfer better, the conditions that promote or hinder transfer, and the instructional methods that support transfer (e.g., Butler, 2010; Butterfield & Nelson, 1991; Chen & Mo, 2004; Gentner et al., 2003; Rittle-Johnson, 2006). In contrast, AOT research assumes that people regularly generalize their learning experiences and finds the lack of transfer from the mainstream cognitive perspective understandable, given the large research base demonstrating that novices rarely make the same connections as experts (Bransford, Brown, & Cocking, 2000). Therefore, the goal of AOT studies is not to obtain transfer (as it is already assumed to occur) but rather to understand the interpretative nature of the connections that people construct between learning and transfer situations, as well as the socially situated processes that give rise to those connections.

Investigating the nature of how people generalize their learning experiences, even when such generalizing results in incorrect performance, should not be misinterpreted as a lack of interest in the goal of ultimately having students achieve mathematical correctness or expertise. An important aim of many AOT studies is to improve the nature of students' generalizing activity. Therefore, AOT is often situated within design-based research, where information regarding how students generalize their learning experiences informs and improves the next cycle of instruction (Kelly, Lesh, & Baek, 2008; Lobato, 2003, 2008a). In fact, mainstream cognitive and AOT perspectives may overlap in the final stages of design-based research when the ultimate goal of the instructional innovation should be met, namely, to support the formation of connections between learning and transfer situations that are more expert in nature. (To see an overlap, qualitative measures would need to be used in the mainstream cognitive approach and the focus would need to be on identifying underlying conceptualizations rather than strategies.) However, in practicality, the goal of research conducted by my colleagues and myself has been to identify increasing levels of sophistication in displays of transfer, much like Minstrell's (2001) facets of students' understanding of physics, where one facet may be indicative of more sophisticated understanding than another, even when both facets represent non-normative or incorrect reasoning. This is because, even after several iterations, we often do not achieve full-blown expertise (perhaps because of limits in the length of instruction or the age of the participants).

To illustrate how AOT research can meet the goal of leading to substantive improvements in both instruction and in the ways students generalize their learning experiences, we revisit the classroom study in which students had generalized slope to novel situations as a difference rather than a ratio (Lobato, Ellis, & Muñoz, 2003). Because the analysis of the transfer interviews revealed that students' conceptualization of slope focused on differences in a single quantity, one goal of the instructional redesign was to necessitate the coordination of two quantities (Lobato, 2005; Lobato, Rhodehamel, &

Q12 Hohensee, 2011, in press; Lobato & Siebert, 2002). Because  
 750 the classroom analysis revealed that the use of tables in which  
 the  $x$ -values increased by 1 in successive rows focused atten-  
 tion on the  $y$ -values, a goal of the instructional revision was  
 to promote multiplicative reasoning between  $x$  and  $y$ -values  
 with data not presented in unit intervals. Because the class-  
 755 room analysis suggested that the language of numbers and  
 recursive number patterns (e.g., “goes up by”) focused atten-  
 tion on single quantities, the next iteration asked students to  
 speak of measurable attributes (e.g., distance, time, speed)  
 and covarying quantities (e.g., 5 s for 7 cm). These and other  
 760 principles were intended to direct attention toward covarying  
 quantities and away from single quantities changing.

As a result, a later iteration in the design-based research  
 resulted in more productive generalizing about slope and linear  
 functions (Lobato et al., 2011; Lobato, Rhodehamel et al.,  
 Q13 in press). The design consisted of an adaptation for younger  
 765 students—seventh graders—and took place in a context in  
 which it (Class 1) could be compared to another class that  
 addressed the same content goals with a different instruc-  
 tional approach (Class 2). Students from both classes partic-  
 770 ipated in postinstructional clinical interviews (Ginsburg,  
 1997) using transfer tasks set in contexts not covered in either  
 class. Qualitative analysis revealed distinct differences in how  
 students reasoned with a table of linear data in a water pump-  
 ing situation (see Figure 3) (Lobato et al., 2011).  
 775 In Class 1, 88% of the students coordinated the two quanti-  
 ties in a way that preserved the multiplicative relationship  
 between the quantities and correctly determined the pump-  
 ing rate (which corresponds to the slope of the function). In  
 contrast, only 33% of students in Class 2 reasoned similarly,  
 780 with the rest of the students engaging in nonmultiplicative

reasoning on the task, including reasoning with differences  
 in only one quantity and reasoning additively.

A critical reader may wonder if we could have shifted  
 to an observer’s point of view for this later iteration of the  
 design-based study and achieved the same goal. After all, it  
 785 was surely a goal of the instruction in Class 1 to coordinate  
 two quantities in a way that preserved the multiplicative  
 relationship between them. In actuality, there had been a  
 more sophisticated goal Aor instruction in Class 1, namely,  
 to form a ratio as a multiplicative comparison (e.g., Kaput  
 790 & Maxwell-West, 1994), and this goal would likely have  
 been used as the standard by which to judge whether or not  
 students’ reasoning counted as transfer, from an observer’s  
 point of view. For example, in the Pool Task, forming a ratio  
 as a multiplicative comparison entails noticing that the water  
 795 values are twice as large as the corresponding time values,  
 obtaining 2 as the ratio, and interpreting it in context as 2  
 gal/min. If we had restricted transfer to this expert goal, we  
 would have missed the way that many students thought about  
 the task. For example, one student used the information from  
 800 the second and third rows, concluded that 4 gal were pumped  
 in 2 min, formed a unit of these two amounts, halved the unit  
 to produce 2 gal in 1 min, and then built up both amounts to  
 check (2 gal in 1 min, 4 gal in 2 min, 6 gal in 3 min, etc.). Al-  
 though many researchers call this *pre-ratio* reasoning (Lesh,  
 805 Post, & Behr, 1988), we believe it demonstrates an advance  
 over the reasoning from the original study and represents a  
 generalization of the students’ learning experiences. Thus,  
 using the AOT perspective in our design-based research  
 helped us meet our goals of uncovering the nature of the con-  
 810 nections that students made between learning and transfer  
 situations at each iteration and using this information to make



Water is being pumped through a hose into a large swimming pool. The table shows the amount of water in the pool over time. The amount of water is measured in gallons. The time is measured in minutes.

Do you think the water is being pumped equally fast over time or is it being pumped faster at certain times? How do you know? How fast is the water being pumped into the swimming pool?

Time in minutes	Amount of Water in gallons
0	0
3	6
5	10
9	18

FIGURE 3 The Pool Task (color figure available online).

incremental and productive changes in how students generalized their learning experiences in each successive iteration.

815 By differentiating AOT from the mainstream cognitive perspective on transfer along five dimensions, I have argued that the AOT perspective (a) emphasizes the interpretative nature of knowing; (b) operates from an actor's point of view; (c) focuses on the transfer of conceptualizations rather than strategies, solution methods, or well-defined actions; (d) is grounded in the use of inductive qualitative methods; and (e) was developed to explore and iteratively improve the nature of novices' generalization of their learning activities in semantically rich content domains. These features make the perspective well suited for investigating particular aspects of the broad array of issues and questions that interest transfer researchers—three of which are explored next.

#### HOW STUDENTS INTERPRET TRANSFER SITUATIONS

830 Just as taking an actor's perspective entails setting aside a predetermined standard for judging the occurrence of transfer, the AOT perspective also sets aside observer assumptions regarding the surface/structure distinction. At the heart of this distinction is a presumption that initial learning and transfer situations share a similar level of complexity. However, what constitutes a surface feature for an expert may introduce a structural complexity for the novice, along a dimension that was unforeseen during the task design process. The use of an AOT perspective can foreground students' comprehension of transfer situations as an object of inspection, which in turn can make explicit particular understandings that are implicit in the researcher's own expertise and can provide useful information for an instructional response.

845 For example, Rebello and colleagues conducted an AOT study to gain insight into the connections that students make between concepts and techniques learned in a calculus class and physics problems that utilize these ideas (Cui, 2006; Cui, Rebello, & Bennett, 2006; Rebello, Cui, Bennett, Zollman, & Ozimek, 2007). To maximize the chances that students would form productive connections, the researchers used straightforward physics tasks and paired each task with an isomorphic calculus problem. However, the physics transfer problems were much more difficult for students than anticipated. In response, the researchers investigated how students experienced the transfer problems. They discovered that students had no trouble carrying out the calculus procedures but found it challenging to decide which variables in the physics situations needed to be integrated or differentiated and to determine the limits of integration. The researchers concluded that what may be conceived, from the perspective of an expert, as a straightforward instance of transfer involving the activation and mapping of new information onto an existing knowledge structure, may in fact involve the creation of new knowledge or knowledge reorganization for students.

The information gained from an investigation of learners' construal of transfer situations can reveal surprising complexities, which can then productively inform an instructional response. For example, when researchers were surprised by the failure of young children to use their counting skills in everyday situations, they used an AOT approach to investigate the children's comprehension of the transfer situations (Hannula & Lehtinen, 2004, 2005; Lehtinen & Hannula, 2006). They discovered that young children often have difficulty structuring the physical world in such a way that the feature of cardinality becomes prominent, especially in naturalistic settings where so many other features compete for their attention (such as the color or shape of objects or the physical movements of the adults who they are mimicking). Once children's ability to focus on numerosity was identified as crucial, the researchers were able to demonstrate that successful transfer of enumeration skills was related to this propensity (Lehtinen & Hannula, 2006). In addition, subsequent interventions capitalized on the insight that what appears to be an obvious and surface feature for an adult (namely, the ability to isolate and attend to cardinality) is a significant structural feature for young children—one that needs explicit development. Consequently, the researchers designed an effective intervention by training Finnish daycare providers to notice and follow up on the moments when children spontaneously paid attention to numerosity in everyday situations, such as cleaning up or free play (Hannula, Mattinen, & Lehtinen, 2005). The intervention led to a long-term effect on the children's tendency to focus on cardinality and to use their counting skills in new situations.

895 These studies demonstrate that transfer situations may be isomorphic to initial learning situations along a particular dimension, yet may include a dimension of complexity that is hidden from the view of an expert until one investigates students' understanding of the transfer situations more closely. Partly, this is because what is challenging for students to understand early on in their development of an idea is often no longer apparent to an adult looking through the lens of sophisticated understanding (Simon, 2006). An actor's point of view, along with the use of qualitative analysis of students' reasoning in transfer situations, can help researchers understand what it takes for students to successfully tackle such conceptual complexities.

#### THE SOCIALLY SITUATED NATURE OF TRANSFER PROCESSES IN CLASSROOMS

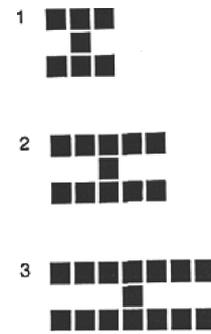
A number of researchers have called for the expansion of transfer processes in order to acknowledge the contribution of social interactions, language, cultural artifacts, and normed practices in the occurrence of transfer (Guberman & Greenfield, 1991; Lave, 1988; Pea, 1989). In response, some researchers have shifted away from attributing transfer to cognitive mechanisms (Beach, 1999, 2003; Bereiter, 1995;

LCHC, 1983; Tuomi-Gröhn & Engeström, 2003). However, this puts the field in danger of losing important insights gained from cognitive models of transfer. Consequently, our recent work from the AOT perspective has offered an explanatory account of the occurrence of transfer in a classroom-based study, by coordinating individual cognitive processes with socially situated processes via the construct of “noticing” (Lobato et al., 2011; Lobato, Rhodehamel, et al., in press). This is in keeping with the AOT position that transfer is a distributed phenomenon across individual cognition, social interactions, material resources, and normed practices.

To illustrate, we briefly outline our explanatory account of the previously described finding that two classes of seventh graders reasoned differentially on a transfer task (see Figure 3). Eighty-eight percent of the students in Class 1 coordinated two quantities in a way that preserved the multiplicative relationship, whereas two thirds of the Class 2 students engaged in non-multiplicative reasoning on the task, including reasoning with differences in only one quantity and additive reasoning (Lobato et al., 2011). To explain why this result occurred, we first analyzed the classroom data to identify what individual students noticed mathematically. By noticing, we do not mean simply “paying attention” but rather the selecting and processing of particular properties, features, or conceptual objects, when multiple sources of information compete for one’s attention. Specifically, students in Class 1 shifted from initially noticing a single quantity to noticing a joined or composed unit of two quantities. In Class 2, students initially noticed differences in a single quantity (the *additive growth* of the function). Then two thirds of the students discovered a relationship between two quantities, which had the potential of becoming a multiplicative relationship. Unfortunately, during the next lesson, students’ attention returned to additive growth and stayed there for the rest of the unit. This is problematic for the development of slope, because slope is multiplicative in nature, not additive.

To understand how these differences in what students noticed mathematically emerged in each class, we examined the role of both students and teachers in the co-constitution of what was noticed through discursive practices (conceived broadly to include gesture, diagrams, and talk). This approach acknowledges Goodwin’s (1994) contention that what people notice “is not a transparent, psychological process, but is instead a socially situated activity” (p. 606). To illustrate the approach, consider the discursive practices that occurred close in time to the shift in noticing back to additive growth in Class 2, as this appeared to be a pivotal event.

The class had been investigating the visual pattern shown in Figure 4. The teacher validated the relationship that two thirds of the students had noticed, namely that the ordinal position of a figure in the pattern (called the “step number”) is the same as the number of squares in each “arm” in the associated figure. As a result, students could determine the number of squares in any figure by multiplying the step number by 4 (the number of “arms”) and adding 3 (the number of squares



1. Study the pattern.
2. Build the fourth term.
3. Make a sketch of the fourth and fifth terms.
4. Use the pattern you discovered to sketch the tenth term.
5. How many units make up the tenth term?
6. Describe any number patterns you notice.

FIGURE 4 The Visual Pattern Task.

in the middle of each figure). The teacher demonstrated how students used the step number to calculate the number of squares in the first three figures of the pattern (as shown in Figure 5). For the statement associated with the third figure (3 · 4 + 3 = 15), she labeled the *step number*, the *number of arms*, and the *middle* (see Figure 5). In an important move, a student directed attention back to additive growth and to a single quantity by asking why they couldn’t just add 11 + 4 (from Step 2 to Step 3), as they knew the growth was 4. The teacher validated the student’s idea, and in a crucial move, *renamed* the 4 in “3 · 4 + 3 = 15” as the *growth* and wrote “growth” beneath “# of arms.” However, the 4 is not the growth; rather it represents the number of arms, which does not change. The teacher conjoined these two constructs by saying that “they use arms for growth here . . . every time it’s growing by 4,” consequently bringing attention back to additive growth. This discursive interchange—beginning with the teacher responding to a relationship students had noticed, followed by a student’s attention-focusing response and an emergent *renaming* move from the teacher—signaled a turning point in the unit, shaping what students attended to mathematically in subsequent visual patterns for the remainder of the unit.

This study, along with subsequent research by Hohensee (2011), demonstrates that the particular mathematical features students notice are conceptually connected to the ways in which students transfer their learning experiences. Furthermore, noticing is socially organized by the joint participation of students and teachers in classroom discourse practices. This exploratory work suggests that it is unlikely for a teacher

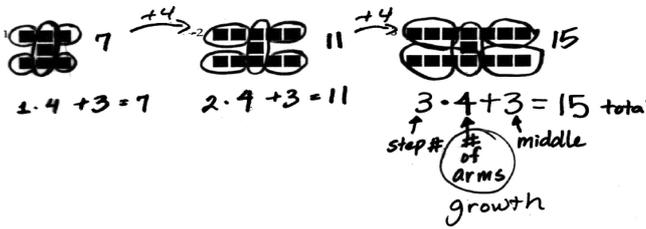


FIGURE 5 The Class 2 teacher's annotations on figures from the Visual Pattern Task.

to simply say, "Look here!" and her students will notice what she targets. Instead, there is a system of elements (discourse practices, mathematical tasks, and the nature of mathematical activity) that work together to bring forth the noticing of particular mathematical features in classrooms.

### THE PRODUCTIVE ROLE OF CONTEXTUAL-SENSITIVITY IN TRANSFER

A common theme in the history of transfer research has been that transfer involves some experience of *similarity* or *sameness* across situations. As the locus of such similarity, the mainstream cognitive perspective has emphasized the encoding and recognition of abstract structures that "delete details across exemplars and avoid contextual specificity so that they can be applied to other instances or across situations" (Fuchs et al., 2003, p. 294). The importance of overcoming context is summarized in a report of the National Research Council: "Knowledge that is overly contextualized can reduce transfer; abstract representations of knowledge can help promote transfer" (Bransford et al., 2000, p. 53). Although the transfer of learning may occur via the formation of abstract representations, it need not be the only way in which transfer occurs. Wagner (2010), drawing upon both the AOT perspective and diSessa's (1993) knowledge-in-pieces perspective, offers an alternative account in which transfer is supported through the incremental growth and organization of smaller elements of knowledge, which are *highly sensitive to context* and are only gradually refined to extend to a widening circle of situations. That is, sensitivity to context—rather than something to be overcome—can play an important role in the transfer of learning.

Specifically, Wagner argues that a concept may have associated with it multiple *concept projections*, which are particular knowledge resources that allow the knower to interpret the situation's affordances in a meaningful way (diSessa & Wagner, 2005; Wagner, 2010). To illustrate, Wagner (2010) presented a case study of a college student, Jason, who formed two concept projections linked with the concept of the law of large numbers (i.e., the idea that larger samples are more likely than smaller samples to be representative of their parent population). In solving problems across a variety of settings, Jason explained some problems in the language of "more or

less well," revealing one concept projection that was particularly useful in contexts involving people's physical skill (e.g., skiing or playing squash). In other problems, Jason spoke in terms of "small groups/large groups" and "more or less often," revealing a second concept projection, which was useful in contexts associated with a statistical interpretation of repeated events (e.g., gender of births in various hospitals or the results of coin tosses). According to Wagner, forming and connecting the two concept projections were the means by which Jason saw the "same thing" across multiple problems. Thus, the case study demonstrates how a single mathematical principle (e.g., the law of large numbers) came to be recognized through a variety of fine-grained interpretive resources that were influenced by contextual factors.

Wagner's account of the productive role of context sensitivity in transfer is consistent with the AOT perspective's emphasis on the interpretative nature of knowledge. From an AOT approach, *structuring* is an active process that occurs through an interaction of contextual affordances, personal goals, and prior learning experiences. *Structuring* is contrasted with the view of extracting a *structure* from a situation, where, as I argued previously, a closer correspondence between the external world and mental structures is often assumed. Relatedly, AOT is rooted in the notion of reflective abstraction (Campbell, 1977/2001; von Glasersfeld, 1990), which is a constructive rather than inductive formulation of abstraction. It focuses on the abstraction of regularities in records of experience in relationship to one's goals and expectations, rather than on regularities inherent in a situation or the encoding of common properties across instances (Goodson-Espy, 2005).

In sum, one way in which a concept may become more robust and general is due to the abstractness of mental representations, which backgrounds contextual details. In an alternative account, generalizability is supported by the increasing complexity of a concept's composition and the context-sensitivity of its parts to accommodate new situations (Wagner, 2006, 2010). From the former perspective, comparing multiple examples can promote the extraction of a common structure (Reeves & Weisberg, 1994). From the latter perspective, having more examples may not necessarily help unless they necessitate a new concept projection or help the learner construct connections among concept projections (diSessa & Wagner, 2005).

### CONCLUDING REMARKS

According to Campione, Shapiro, and Brown (1995), "it is not clear that a single theory could exist to cover the range of phenomena to which the term [transfer] might be, and has been, applied" (p. 35). In this article, I have argued that the AOT perspective emphasizes the interpretative nature of knowing and the transfer of learners' underlying conceptualizations, relinquishes a predetermined standard for judging

1095 what counts as transfer and draws upon inductive qualitative  
 methods. These characteristics make the perspective well  
 suited for investigating how learners construe meaning in  
 transfer situations, understanding the often unexpected con-  
 1100 nections learners make between learning and transfer situa-  
 tions and then mining this information to improve instruc-  
 tional responses, accounting for the socially situated nature  
 of transfer processes, and understanding how sensitivity to  
 context can be useful in the generalization of learning. Cor-  
 1105 respondingly, there are many aspects of the phenomena of  
 transfer for which other perspectives are better matched.  
 For example, from a situated cognitive perspective, Engle,  
 Lam, Meyer, and Nix (2012/this issue) explore the role of so-  
 cial framing in the transfer of learning in classrooms. From  
 a preparation for future learning perspective, D. Schwartz,  
 1110 Chase, and Bransford (2012/this issue) develop and explore  
 the construct of adaptive transfer. And from the mainstream  
 cognitive perspective, Nokes (2009) proposed a unified the-  
 ory of how multiple transfer subprocesses (such as constraint  
 violation, analogical reasoning, and knowledge compilation)  
 1115 interact with each other and with particular task conditions.

Viewing these transfer approaches as designed objects  
 that provide different information for different purposes  
 is analogous at a metalevel to the overarching message  
 from the research on transfer-appropriate processing (Morris,  
 1120 Bransford, & Franks, 1977). Countering the accepted view  
 that superficial levels of processing were always inferior to  
 semantic processing, Morris et al. demonstrated that the na-  
 ture and retention of memory depends not just on the level of  
 processing but on how well the conditions of learning activ-  
 1125 ities match the goals and purposes of the retrieval activities.  
 Similarly, rather than judging any one transfer model in an  
 absolute sense, there is value in differentiating various ap-  
 proaches to gain a better understanding of the features and  
 methods of each approach relative to its goals and purposes.

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# Knowledge to Go: A Motivational and Dispositional View of Transfer

David N. Perkins and Gavriel Salomon

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Knowledge to Go: A Motivational and Dispositional View of Transfer  
*David N. Perkins and Gavriel Salomon*

## Knowledge to Go: A Motivational and Dispositional View of Transfer

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We synthesize ideas from the foregoing articles in this special issue and from the broader literature on transfer to explore several themes. In many ordinary life circumstances, transfer proceeds easily, but formal learning often shows much less transfer than educators would like, making failure to transfer a focus of investigation. Transfer, like any complex cognitive performance, benefits from motivational and dispositional drivers, an aspect of transfer not much discussed in these articles but inviting attention. Episodes of transfer can be analyzed according to a detect–elect–connect model: detecting a potential relationship with prior learning, electing to pursue it, and working out a fruitful connection. These three “bridges” are somewhat independent; ways in which each of them succeed and fail are detailed, drawing on the contributed articles and the broader literature. Finally, insights from this collection of articles and elsewhere put educators in a position to teach for transfer more effectively, but shifts of mind-set about the nature of knowledge and learning are required.

Schools are supposed to be stopovers in life, not ends in themselves. The information, skills, and understandings they offer are knowledge-to-go, not just to use on site. To be sure, often Monday’s topics most conspicuously serve the Tuesday problem set, the Friday quiz, or the exam at the end of the year. However, in principle those topics are an investment toward thriving in family, civic, cultural, and professional lives.

Unfortunately, considerable research suggests that much of the knowledge-to-go served up by schools does not “go” that far. Besides just plain forgetting, people commonly fail to marshal what they know effectively in situations outside the classroom or in other classes in different disciplines. The bridge from school to beyond or from this subject to that other is a bridge too far.

This, broadly, is the challenge of transfer of learning as encountered by formal education. It is a challenge taken up by all of the foregoing articles. For instance, Chi and VanLehn (2012/this issue) makes the “failure-to-transfer phenomenon” central to her analysis. Lobato (2012/this

issue) remarks that “people notice the transfer of learning when it *doesn’t* happen” (p. XX). Lobato also cautions that even when exactly the transfer we want does not occur, other pertinent kinds of transfer may. Among others, the work of Richland, Stigler, and Holyoak (2012/this issue) reminds us that transfer includes not just fruitful transfers missed but unfruitful ones made. Focusing on the case of mathematics learning in junior colleges, Richland et al. document particularly egregious examples of negative transfer, where students commonly apply mathematical routines to new situations quite inappropriate to them and with little attention to the plausibility of the results.

With all these negatives, sometimes transfer seems like the hopelessly slow child of learning. But not so for the contributors to this issue. All the articles take an optimistic stance. Their common motif is not *whether* significant transfer of learning can occur but *under what conditions of learning*. They offer perspectives on those conditions, even as they often caution that business-as-usual in classrooms does not do a very good job of meeting them.

It’s our responsibility and pleasure to comment on these articles, identifying themes and patterns. The organizers of this issue also have encouraged us to offer our own ideas on

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knowledge-to-go. Accordingly, we begin our discussion by examining the meaning of transfer of learning as expressed by the contributing authors. Then we outline a framework for analyzing transfer. Then we offer several sections drawing on the contributing authors to discuss when and why transfer comes easy or comes hard. We conclude with an assessment of the prospects of teaching for transfer.

## BROAD MEANINGS FOR TRANSFER OF LEARNING

What counts as transfer of learning in contrast with just plain learning? The question arises because all learning involves transfer in some sense. Evidence of learning always entails the learner doing something at least later and under another set of conditions, if not elsewhere, informed by what has been learned; otherwise there would be no basis to claim that learning had occurred. On this reading, transfer has an *inclusive* meaning, always part of learning and a matter of degree—how much later, how far elsewhere, and how different the conditions under which it is displayed. However, transfer as researchers usually use the term takes on a *contrastive* meaning—successful initial learning positively influencing performance on a later occasion and with a different appearance (transfer) versus not influencing (failure to transfer). Yet another case is negative influence, generally called negative transfer.

But what counts as “influence”? The term *transfer* itself suggests a simple pattern of learn-it-here, apply-it-there. However, the contributors to this issue emphasize that transfer should be viewed far more broadly. Chi and VanLehn (2012/this issue) and Lobato (2012/this issue) both pick up a warning from Lave (1988) about the limits of the “two-problems” transfer paradigm where subjects tackle one problem and then face another with different surface characteristics but a similar deep structure. Although this work has proved revealing (e.g., Gick & Holyoak, 1980, 1983), many scenarios of transfer do not resemble a two-problem paradigm. But it cannot be dismissed as a mere laboratory construct. Chi and VanLehn point out that some typical patterns of instruction in schools look very much like an expanded version of the two-problems paradigm.

A broader pattern of transfer is the direct application of an explanatory concept to new instances well removed from the initial learning. For instance, imagine some students studying the law of supply and demand. The learning activities include using the law to interpret several diverse cases. A couple of weeks later a student goes supermarket shopping and gets annoyed with the surprisingly high price of oranges. Puzzling over the situation, the student relates this to a cold winter in Florida that killed much of the orange crop, lowering supply and driving up prices.

Such direct applications at some distance from the initial learning are also a limited scenario. Lobato (2012/this issue)

notes that transfer situations can be sites for invention and reorganization, not just carrying forward and plugging in. Schwartz, Chase, and Bransford (2012/this issue) contrast routine transfer with adaptive transfer, which involves not just applying but adapting and revising prior knowledge in the context of transfer.

For instance, imagine another student in the group that learned the law of supply and demand. This student, in the midst of a messy social life, ponders love and the reciprocities it involves. The student suddenly wonders whether such personal exchanges somehow reflect the law of supply and demand and mulls over the idea. “It’s hard for me to find a girlfriend I really like,” he thinks. “There’s so much competition. That’s demand. Well, but just saying it’s hard, is that like a price? Well, it’s kind of like cost-of-effort maybe. But look, this isn’t a market really, or if it is kind of, that’s certainly not a nice way to think about it.” He sees some similarities and differences. The mismatches as well as the matches reveal more about the reach of the law of supply and demand itself.

This illustrates “backward transfer,” where dealing with the current situation leads to revisionary adaptations in a prior conception (Hohensee, as cited in Lobato, 2012/this issue). For instance, Ross and Kennedy (1990) discussed how problem solvers addressing new problems by analogy with previous ones constructed generalizations of the approaches to the previous problems, developing a more flexible repertoire. More broadly, Engle, Lam, Meyer, and Nix (2012/this issue) draw on the notion of intercontextuality, where learning contexts can refer forward to potential transfer contexts and vice versa, with enough linkages making them perceived as one large context.

Lobato also warns of the tendency to evaluate transfer of learning only from an expert’s perspective: Are students grasping and using the big ideas anointed by the discipline? The economist might be happy with the price of oranges example and maybe even the love example. However, other students might be taking away something more modest but still useful—for instance, simply a broad tendency to question where prices come from. Lobato and others recommend an actor-centered perspective, asking what sorts of transfers figure in learners’ learning and how, even if they aren’t the anointed ideas.

Finally, not just payoffs in the moment but “preparation for future learning” is an important and documented benefit of transfer (Bransford & Schwartz, 1999). In particular, learning experiences involving inventive exploration of the topic can deepen learning from later, more presentational learning of the topic, even if the inventive explorations do not in themselves yield a very good understanding.

All this adds up to an appropriately flexible conception of transfer. However, we note one way in which the conception is confusingly flexible: There is considerable interpretive latitude about whether to frame some situations as failure to transfer or failure of initial learning. For instance, Richland et al. (2012/this issue) discuss how some junior college

170 students cannot place a simple fraction like  $\frac{4}{5}$  on the  
 number line, along with related mishaps. They treat this as  
 failure to transfer from initial conventional instruction that  
 successfully establishes certain kinds of routine compu-  
 175 tational knowledge. However, other researchers might say  
 that the initial instruction failed—surely it was *intended* to  
 develop a general understanding of fractions, but the learning  
 may have been extremely situational and bound to fractions  
 routines. More generally, Chi and VanLehn (2012/*this issue*)  
 180 notes that one of the most prevalent explanations for failure  
 of transfer is that the learners did not achieve a sufficiently  
 deep understanding of the content in the first place. Such  
 cases always allow an alternative description: They weren't  
 failures of transfer but failures of initial learning.

no s

How is it that contrasting descriptions of the same situa-  
 185 tion arise? Because different researchers can have different  
 conceptions of what applications fall within the intended  
 scope of the initial learning (where failure indicates failure  
 of the initial learning) and what applications reach markedly  
 beyond it (where failure indicates failure of transfer). To be  
 190 sure, further empirical investigations might help to clarify  
 the situation with finer grained accounts of the intended ini-  
 tial learning and the learning and transfer actually achieved.  
 However, where to draw the line between a straightforward  
 extension of initial learning and true transfer remains some-  
 195 thing of a judgment call. Much may depend on one's judg-  
 ment of the “distance” between what is learned and the do-  
 main of application. Imagine, for instance, a history unit on  
 the decline of Rome that also touched on comparisons and  
 contrasts with more recent cases such as the Ottoman Empire  
 200 and the British Empire. Later, students are asked to analyze  
 the case of the USSR. Would this count as a straightforward  
 extension? After all, the students had practiced on other em-  
 pires. Or would it count as transfer? After all, the students  
 had not taken up the USSR or other near-contemporary cases  
 205 before. Clearly there is no absolute answer. Accordingly, al-  
 ternative descriptions of some situations as failure to transfer  
 or failure of initial learning are likely to persist.

On the positive side, when the extrapolations from initial  
 learning clearly reach well beyond the straightforward, no  
 210 such ambiguity surfaces. If the students' study of the decline  
 of Rome had not ranged beyond Rome at all, applications  
 to the USSR clearly would count as transfer because of the  
 “distance” from the initial learning—more precisely, the  
 surface and, to an extent, deep-structure (dis)similarities  
 215 between the two. Engle et al. (2012/*this issue*) discuss a high  
 school biology teacher encouraging students to make links  
 beyond the immediate unit, and outside of school, and to  
 chemistry class; a student generating a metaphor between the  
 atrium of the heart and an atrium in the school; and students  
 220 finding links between three different units. Our examples of  
 the price of oranges and of love both involve reaches well  
 beyond the initial learning; they require the incidental notic-  
 ing of possible connections while engaged in other matters  
 entirely.

With an emphatically broad and flexible conception of 225  
 transfer in view, we turn to a perspective on how transfer  
 happens.

### THREE BRIDGES FOR TRANSFER OF LEARNING

Let's look back at the student relating the high price of or- 230  
 anges to the chilly Florida winter and the student pondering  
 love as a dynamic of supply and demand. To bring it off, these  
 students have to build three mental bridges. In mnemonic  
 spirit, let's call them *detect*, *elect*, and *connect*. The student  
 in the supermarket has to *detect* a possible link between the 235  
 high price of oranges and the law of supply and demand,  
*elect* to explore the link, and *connect* the law to the particu-  
 lars of the orange crop. The student thinking about love has  
 to *detect* a possible relationship with supply and demand,  
*elect* to pursue the idea, and *connect* the law effectively to 240  
 this very nonmonetary sort of situation, certainly more of a  
 stretch than the orange case (remember, *connect* can mean  
 developing insightful contrasts, not just similarities). As we  
 see later, depending on the circumstances, any of the three  
 bridges can be a bridge too far. 245

In general, it's natural to think in terms of transfer when  
 one notes contextual or structural gaps of detect, elect, or  
 connect between earlier learning and the moment of inter-  
 est. When the moment of interest appears seamless with  
 what's gone before, this would not be called transfer in the 250  
 contrastive sense discussed earlier. Imagine for instance a  
 supply-and-demand quiz featuring the kinds of problems stu-  
 dents had just discussed in class. Good performance on the  
 quiz would count as a sign of initial learning rather than a  
 demonstration of transfer. 255

We relate detect, elect, and connect to the larger literature  
 on transfer in later sections, for now profiling them broadly.  
 We view detect, elect, and connect as functions to be ful-  
 filled one way or another on any occasion of transfer . . .  
 but not always fulfilled in the same way, much as, to make 260  
 an analogy, one might come to a decision by means of a  
 pro-con list or reviewing how similar decisions worked out  
 previously or a quick intuitive judgment. The three bridges  
 get built in various ways by the business-as-usual of cog-  
 nition noted throughout this collection of articles—memory 265  
 retrieval by similarity, pattern recognition, the acquisition of  
 routines, surface and deep coding, the consequent formation  
 of schemas, analogizing, and so on.

In keeping with a grab bag of contributing processes, the  
 three bridges sometimes occur serially but sometimes virtu- 270  
 ally simultaneously. In the episodes about oranges and love,  
 the bridges get built in serial succession—detect the occa-  
 sion, elect to pursue it, work out the connection. However,  
 transfer commonly occurs through sudden recognitions of  
 significance or of unexpected absence or anomaly understood 275  
 in an instant that fold together detect, elect, and connect.

Also, the three bridges do not presume conscious awareness of making a link. It's important to recognize that considerable transfer, maybe most transfer, occurs automatically. This can be the case even when people are alert and attentive to what they are doing. For instance, Day and Goldstone (2011), using the two-problems paradigm, demonstrated marked transfer from one computer-based manipulative task to another involving simple dynamic systems, with many subjects not reporting any awareness of the relationship. Moreover, in a version of the experiment where subjects were required to formulate explicitly the relationship between the tasks, this *undermined* rather than enhanced transfer.

Relatedly, Salomon and Perkins (1989) distinguished between high-road and low-road transfer. High-road transfer involves deliberate reflective processing, whereas low-road transfer depends on pattern recognition and the reflexive triggering of routines. The high-road/low-road contrast relates to dual processing models of cognition that juxtapose deliberative with automatic processing (e.g., Epstein, 1994; Evans, 2008; Stanovich, 1999). Here we note that the bridges of detect, elect, and connect can get built by both deliberative and automatic processes. For instance, one can detect a connection through mindful scouting for prior knowledge that might help (high road) or simply through noticing a fit (low road). High-road and low-road processing can mix. For instance, one might systematically scout for a helpful link to prior learning (high road), and, locating a lead, find that the rest falls into place like a sudden insight (low road).

Finally, the ideas about detect-elect-connect and high-road/low-road provide a frame for discussing the place of motivations and dispositions in transfer of learning. High-road episodes of detect, elect, or connect by definition demand extended cognitive effort and hence require significant motivational or dispositional drivers. For instance, to deliberate about the high price of oranges, our student in the supermarket would need to be curious about it, or perhaps deciding whether to complain to the manager about the cost unless it seemed justified. The student pondering love would be worried about personal relationships.

The story is different for low-road episodes of detect, **change "deciding" to "decide"** unfold relatively automatically of habit rather than this does not mean that motivation and dispositions play no role. For instance, driving a moving van when you have only driven cars before can require courage, even though most of the mechanics of driving automatically transfer.

We distinguish the three bridges toward illuminating the nature and mechanisms of transfer further in the following pages, drawing particularly on the articles in this issue. We do not expect the authors to have employed these concepts themselves, but their investigations reveal much about the three bridges, when they carry traffic, and when they fail. Also, the place of motivation and dispositions in transfer is not prominent in the articles collected here. Only Schwartz et al.

(2012/*this issue*) directly discuss motivational and dispositional factors. Other authors bring forward matters such as understanding, meaningfulness, and expectations that clearly would contribute to the motivational and dispositional side of the story but do not discuss it much as such. Accordingly, we take the opportunity to do so throughout this article.

## EASY TRAVELS FOR TRANSFER OF LEARNING

As noted earlier, researchers study transfer of learning because their hope for knowledge-to-go often does not pan out. For balance, it's useful to recognize that transfer is far from the wingless dodo of human cognition. Transfer routinely succeeds in a wide range of cases. A better perspective on what makes transfer hard comes from noting cases where transfer proves easy.

For example, comparison is an everyday kind of cognition that inevitably involves elements of transfer. Richland et al. (2012/*this issue*), distressed about students' poor transfer of basic concepts in arithmetic, remark that the very same students almost certainly readily "compare the plots of movies, the sources of difficulty in different videogames, the reasons why various romantic relationships have succeeded or failed." Richland et al. note how everyday understanding in terms of cause-effect relations supports such transfer. Chi and VanLehn (2012/*this issue*) suggests **no s** ~~that~~ transfer almost always happens when surface features match, and surface features often correlate with deep structure.

Bereiter (1995) emphasized several areas where for most learners transfer occurs so routinely and reliably that no one studies it as transfer—reading, writing, routine arithmetic skills, and the use of prior knowledge for further learning building directly on the same ideas. The three bridges help to explain why. For instance, text directly cues reading, one has both the habit of reading text and generally a reason to read texts one picks up, and the basic skills are established. In other words, the bridges of detect, elect, and connect are solidly in place.

The world of ready transfer goes well beyond literal comparisons. When William B. Yeats in his "Sailing to Byzantium" compares an aged man to *a tattered coat upon a stick* or Shakespeare has Romeo say *Juliet is the sun*, we generally understand such tropes effortlessly. Nor do we have to turn to classic authors for examples. Readily understood metaphors saturate everyday speech. Although some are idioms, others, freshly coined, still communicate easily. In terms of the three bridges, listeners do not need to detect a potential relationship, because the speech or text already directly cues it. Engagement in the interaction makes electing to interpret the metaphor the default and virtually reflexive course of action. Listeners only have to connect across the gap of meanings posed by the metaphors, a mental bridge set up to be readily constructed because speakers speak with accessibility in

385 mind. Note also that on the production side, coming up with casual metaphors is a common part of everyday conversation.

Humor is another everyday area where transfer thrives. Spontaneous humor commonly involves category miscegenation of varied sorts. Consider this classic linking of well-motivated homicide and suicide:

390 *Lady Astor:* If you were my husband, I'd poison your tea!  
*Winston Churchill:* My dear, if you were my wife I'd drink it.

To produce such a quip, Churchill had to detect the opportunity, elect to pursue it, and connect a poisoning scenario with one that paradoxically welcomed it, all in a flash. Most of us are not as word-nimble as Churchill, but we readily understand even if we don't produce. Also, quips of one sort or another are commonplace with certain people in certain social settings, like cocktail parties—the settings prime the reach to detect, elect, and connect, presumably with the help of schemas for various quip structures.

400 Lest metaphors and jokes seem too unserious (but, of course, they are often very serious), social rules and their violations are another area of ready transfer. We often carry norms of behavior from home to workplaces or social activities, and sometimes mistakenly carry them to other countries and cultures where they do not fit.

One could go on, but perhaps these diverse examples suggest that, if transfer sometimes comes hard, it also may come easy. Lobato (2012/*this issue*), discussing the actor-oriented perspective on transfer, emphasizes that the traditional approach to investigating transfer tends to “underestimate instances of the generalization of learning.” Indeed so! Transfer comes easy when prior learning, surface cues, direct cueing, situational priming, and preselection of targets for accessible consumption as in metaphor and humor support detect–elect–connect.

The question remains why transfer has proved such a Gordian knot in formal education. We pursue this theme by visiting each of the bridges as individually necessary and mutually sufficient conditions for transfer. It would seem most natural to address *detect* first, then *elect*, and then *connect*, as the bridges often get built sequentially. However, the contributions of the authors to the special issue suggest a different order of discussion. The contributions address *connect* most directly. Accordingly, it's more orienting to examine first the final bridge of *connect*, and then consider how *detect* and *elect* lead up to it.

### CONNECTING—SOMETIMES A BRIDGE TOO FAR

430 In the detect–elect–connect framework, *connecting* addresses the challenge of finding a relevant relationship between initial learning and the transfer situation, with detect and elect already taken care of one way or another. In some

classrooms and some everyday circumstances, developing the connection is the principal problem. Participants already understand that they are supposed to apply a prior learning and feel motivated. Even so, the connection may prove hard to see. A familiar idiom testifies to connection problems: “What's that got to do with the price of oranges?” . . . or the price of eggs, or tea, or fish. We make this complaint when someone has said something supposedly relevant, directly cueing a connection we want to understand . . . but we don't get it. The nature of connections and the challenges of working them out are matters richly addressed by the contributors to this issue.

Perhaps the most commonly mentioned basis for transfer is sufficiently deep understanding developed in the original context of learning. Such an understanding commonly is said to take the form of schemas representing the knowledge in question. Transfer requires coordinating the schemas with new situations. This process may constitute a straightforward application, what Schwartz et al. (2012/*this issue*) call routine transfer, as noted earlier; or it may involve significant reconstruction of the source schemas and the target situation to bring them into an illuminating relationship, what Schwartz et al. call adaptive transfer. As noted earlier, the price-of-oranges example illustrates the former, the love example the latter.

Discussion of schemas often includes a contrast between surface and deep structure. As Chi and VanLehn (2012/*this issue*) puts it, for real understanding and good prospects of transfer, learners need to learn to “see” through surface features of situations to discern underlying patterns. Chi and VanLehn observe that, in some everyday areas, this seems quite easy—for instance classifying diverse kinds of behavior as drunken despite very different surface characteristics. Richland et al. (2012/*this issue*) emphasize how causal schemas support making sense of everyday cause–effect relationships. Constructing the relationship does not necessarily mean that the initial learning yielded schemas fully prepared for the stretch. Richland et al. (2012/*this issue*), among others, note that schemas often get constructed as a side effect, as people apply a solved source problem to a new problem.

Lobato (2012/*this issue*) warns that such relationships may not be the same from person to person, neatly determined by the source knowledge and target situation. The constructed connection can take different particular forms while reflecting the same broad principles. Lobato illustrates with case studies from Wagner (2010) concerning the law of large numbers, where subjects applied the principle to solve the same problems effectively but in very different ways. Lobato relates this to “transfer-in-pieces,” an alternative to a schema-based view of transfer also drawn from Wagner (2006). Rather than the development of abstract schemas, Wagner argues that transfer emerges from the gradual accumulation of smaller elements of knowledge, rooted in particular contexts, and gradually extended to a great range of situations.

add comma

no s

comma

comma

490 These ideas help to explain how the bridge of connect  
 might get built—that is, how people actually work out relationships between source knowledge and target situations. However, connect sometimes is a bridge too far. Chi and  
 no s VanLehn (2012/*this issue*) observes how in classic work on  
 the two-problems paradigm in transfer, as well as considerable  
 495 work on science learning, often students do not see  
 through the surface. Novices tend to group problems by surface features such as inclined planes or falling bodies and approach them in routine procedural ways associated with  
 those characteristics. Experts see past the surface and focus  
 500 on underlying physical principles such as conservation of energy, grouping problems quite differently. Chi and VanLehn's analysis contrasts same–same cases, where surface and deep structure between source and target both align and transfer generally occurs; different–same cases, where different surface  
 505 structure masks similar deep structure, blocking transfer; and same–different cases, where similar surface structure lures inappropriate transfer despite different deep structure.

For another kind of difficulty, Richland et al. (2012/*this issue*) suggests that junior college students have difficulty with  
 510 rather elementary mathematical understandings in part because the connective structure of mathematics is not causal but formal. Learning experiences in mathematics that foster analogical reasoning might aid in developing appropriate causal and formal schematic structures.

515 Difficulties with building a connection become particularly salient when tasks provide detect and elect directly by asking learners to apply prior knowledge to specific problems. Even with nothing but connect to worry about, learners can easily fail. One case mentioned earlier was inability  
 520 to place a fraction on a number line. For another example from Richland et al. (2012/*this issue*), the authors also report students' responses to the question, "Which is greater?  $a/5$  or  $a/8$ ." Results were extremely disappointing, virtually at chance level.

525 Another example comes from the control group of a study by Chase and Schwartz (as cited in Schwartz et al., 2012/*this issue*) of eighth-grade students learning about density, one group through a tell-and-practice condition, another in a condition that required students to invent their own formula, with  
 530 a direct introduction to the official formula later. The question was whether the students would catch on to the ratio structure of density. In the "invent" condition, about half of them showed this understanding on later directly posed problems. In the tell-and-practice condition, most did not, especially  
 535 when the tell-and-practice condition featured concrete rather than abstract illustrations, a difference that did not matter in the "invent" condition.

Such examples reveal how easily straightforward instructional paradigms fall short of building a basic understanding.  
 540 As discussed earlier, whether this is called failure to transfer or simply superficial initial learning is a descriptive choice for researchers. Either way, the initial learning comes up wanting.

Such examples also illustrate how laboratory and academic settings for transfer tend to obscure the role of motivations and dispositions "in the wild," even as they disclose the role of deep structure or related constructs. In virtually all the foregoing cases, learners are directly asked to undertake tasks, motivated by compliance and rewards such as subject fees or course-completion credits. Emphasis falls on learners' ability to make the desired connections rather than their motivation or disposition to do so. We continue this theme in the following sections.

#### DETECTING—SOMETIMES A BRIDGE TOO FAR

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In the detect–elect–connect framework, *detecting* means discerning the possibility of a connection. This sometimes occurs on the fly out of the blue, as with the stories of the price of oranges or love. The themes from the previous section on connecting certainly have implications for the bridge of  
 560 detecting. Schemas, causal networks, or the knowledge elements of transfer-in-pieces can help to set the learner up for recognition of possible connections well beyond the immediate context of initial learning. However, catching possible  
 565 connections on the fly is a fundamentally different challenge than working them out once identified. The student noticing the high price of oranges might easily never even think of trying to relate it to the law of supply and demand, no matter whether the student could succeed in doing so.

In general, circumstances inviting interpretation from this  
 570 or that perspective come up all the time in our lives. We can hardly expect to catch more than a small fraction of the opportunities. Moreover, the most promising circumstance for detect—high surface similarity—may favor superficial rather than deep connections, because there is less press to  
 575 construct an abstract relationship between the source and target situations (Byrge & Goldstone, 2011; Day, Goldstone & Hills, 2010; Goldstone & Sakamoto, 2003).

Detect has its own processing demands somewhat different from connect. For instance, Ross (1984, 1989)  
 580 examined a version of detect through the concept of reminders—automatic recollections of previous specific episodes of learning in a new situation—finding the retrieval process dominated by the surface content of the prior learning. Gentner, Rattermann, and Forbus (1993) offered  
 585 evidence that, after surface properties drive retrieval, comparison can readily draw out deeper relational properties, the sort generally thought to be important in making a good connection. Moreover, both expertise and more intensive learning activities favor some initial retrieval by deeper  
 590 structural characteristics.

Missing the very possibility of a connection figures commonly in failure to transfer. In the classic work of Gick and Holyoak (1980, 1983) on transfer between problem analogs, the earlier experiments involved telling subjects directly that  
 595

the first problem they considered might bear on the second (transfer) problem. This hint never involved substantive information about the nature of the connection. However, in later experiments, the researchers systematically included or dropped the hint, virtually always finding a substantial impact. They explicitly framed noticing the possibility of a connection to the target problem as an additional processing requirement (Gick & Holyoak, 1980).

The discussion of “inert knowledge” by Bransford, Franks, Vye, and Sherwood (1989) also offers clear cases of detection problems. The authors emphasize that knowledge can be learned and understood but still inert, not activated in relevant contexts. In one experiment, subjects learned ideas about water as a standard of density, solar-powered airplanes, nutrition, and other matters. One group studied for information; the other group learned in the context of thinking about a jungle journey. Both groups showed good retention on direct probes. The subjects also engaged in planning a desert expedition. The group that had learned for information made little use of it; the knowledge was “inert” in the jungle journey context. In contrast, subjects who had learned in the active planning context of the jungle journey made rich use of the knowledge for the desert expedition.

Some of our own research shows that people have acquired thinking skills that are often inert. As part of an investigation into thinking dispositions, Perkins and colleagues studied adolescents’ comments on stories including everyday problem solving and decision making (Perkins, Jay, & Tishman, 1993; Perkins, Tishman, Ritchhart, Donis, & Andrade, 2000; Perkins & Ritchhart, 2004). The stories included lapses of good thinking, such as failing to examine the other side of the case or neglect of more imaginative options. The studies disclosed that subjects rarely detected a lapse on their own, even though they were asked and encouraged to evaluate the thinking in the story and despite participating with interest. However, the subjects demonstrated prior learning of the skills and their importance: Many of the subjects recognized as problems when they were pointed out that virtually all the subjects had the skills to repair the lapses, for instance, generating reasons on the other side of the case or more imaginative options. In sum, the biggest problem was *detecting* possible lapses in the first place. In addition, detecting did not correlate with short-form measures of intelligence. All this contrasts sharply with the tendency to attribute shortfalls of thinking primarily to limitations in intelligence, thinking abilities, or strategic repertoire.

Relatedly, Klaczynski (2005) reported a series of studies of reasoning in adolescents chosen to have strong beliefs in some area, for instance, a religious denomination. Subjects read arguments or brief reports of scientific investigations containing flaws. The readings were edited so that the conclusions would conflict, align, or be neutral with respect to the beliefs. The research revealed that subjects commented insightfully on the flaws far more often in the belief–conflict situation than the other two. The explanation

reflects a dual processing perspective: The statements contrary to subjects’ general beliefs activated mindful deliberate processing, quickly leading to the discovery of flaws. Going back to Berlyne (1965), the conflict situation is sufficiently unsettling to arouse strong motivation to re-settle the conflict. In the other conditions, detection became the “bridge too far”—why look critically when you can readily accept what’s being said?

In further studies, instructions were added to motivate careful thinking: If subjects did not reason clearly and carefully, they would need to meet with researchers later in the week to justify their responses. This direct cue to think things through greatly increased detection of flaws regardless of condition, although subjects’ reasoning still proved far more elaborate in the belief–conflict condition.

As noted earlier, we are bringing the detect–elect–connect contrast to this discussion, not expecting to find it in the contributed articles. However, some of the authors show concern with the prospects of transfer well beyond the original occasions of learning and in situations where prior knowledge is not directly cued.

Engle et al. (2012/*this issue*) foreground a contrast between expansive and bounded framing of the original learning. Expansive framing emphasizes the meaningfulness and usefulness of what’s being learned and its potential to relate to a range of other circumstances. Bounded framing treats what’s being learned as for the unit, for the class, for the quiz. The broad teaching/learning moves that characterize expansive framing plainly put learners in a better position to detect opportunities for transfer. They include cultivating expectations that what’s being learned will speak to related settings; treating previous learning as continuously relevant, treating the use of prior learning as desired socially; and, broadly speaking, encouraging students to see themselves as the agents of their own learning and use of knowledge.

The verb “see” with its tone of perceptual immediacy suggests detecting possible connections. Recall how Chi and VanLehn (2012/*this issue*) emphasizes the importance of “seeing” the deep structure in situations. This relates to the earlier distinction between high-road (deliberate) and low-road (automatic) processing. For the expert, the deep structure has become almost automatically available.

Schwartz et al. (2012/*this issue*) remind us of classic research on mental sets and functional fixedness, which demonstrates how problem solvers can be blinded by initial associations and ways of framing problems (Dunker, 1945). For instance, problem solvers could easily fail to detect a nearby paper clip as a potential tool for fishing a ring out of a drain, even though they would easily act on the suggestion.

In general, seeing what one might think is straightforwardly “there” cannot be taken for granted. Hannula and Lehtinen (2005; Lehtinen & Hannula, as cited in Lobato, 2012/*this issue*) examined how young children apply counting to naturalistic situations. These investigators discovered

put an -ing verb such as "using"

no s

add commas  
before and after  
"on the other"

that children who can count perfectly well often do not find number of items a salient feature. The authors devised and tested an intervention that cultivated more alertness to numerosity. Their work demonstrated, on one hand, that detect can be the bridge too far and on the other that interventions can directly address detect. In accordance with Lobato's perspective, their work argues for the importance of an actor-oriented approach to transfer that examines carefully just what's going on.

### 715 ELECTING—SOMETIMES A BRIDGE TOO FAR

In the detect–elect–connect framework, *elect* means choosing to pursue a possible connection. The student noticing the high price of oranges might muse, "Maybe it has something to do with that supply–demand thing," but then drift along to something else. Just as we miss many opportunities for transfer altogether, many others we do not bother to pursue. Although, as argued earlier, motivations and dispositions play a role in all three of detect–elect–connect, *elect* takes on special status as a pivotal point where the learner either moves forward or turns aside.

More provocative than simply letting a possible connection go are cases where alternative entrenched ways of responding and contrary motives hijack potential transfer. As to entrenched ways, Langer and Imber (1979) showed how "practice makes imperfect" as it leads to overlearned routines, thus mindlessly treating new problems as if they are familiar ones. As to contrary motives, just think of why Milgram's (1963, 1974) subjects would continue harming another individual being, motivated to satisfy a scientific authority, or why otherwise honest students cheat on exams. Instead of the student in the supermarket, imagine the person who has learned a new exercise plan. The person understands perfectly well the routine to be followed. Unfortunately, at the critical moments, old aversions capture behavior, accompanied by convenient rationalizations like "I'll let it go just this once" or "I'm easing into it." Likewise, when people face moral dilemmas or find themselves tempted by impulsive but unwise actions, they recognize the choice but often the "dark side" wins.

To mention some of our own work again, Salomon (2006) reported how the initially positive impact of peace education programs on perceptions and attitudes quickly dissipates in the face of contrary sociopolitical forces. The problem is that after participants return to "life as usual," social contexts erode the mind-sets and behaviors that have been acquired. It's not that the ideas have been forgotten or become obscure in a conceptual sense. Rather, commitment to them falters in the face of counterforces. The fact that the changes of attitude and perception have not disappeared is revealed by the repeated finding that they can be revived by means of reflection, peer teaching, or role playing.

One might question whether the bridge of *elect* should figure in the story of transfer at all. It could be said that *elect* was just a matter of choice and not about building the cognitive bridges of *detect* and *connect*. However, leaving *elect* out of the picture would impoverish the idea of transfer. Remember that knowledge-to-go is the aim. A causal account of why knowledge does not "go" needs to recognize that potential transfers often face sharp competition from other responses and other motivations. Areas of hot cognition like peace and war are not the only examples. For a more academic case, research on physics learning regularly reveals that students' technical understanding competes with and often loses out to everyday intuitive misconceptions. An elegant example comes from Marcia Linn (2002), who wryly quoted a student's view of a Newtonian principle: "Objects in motion remain in motion in the classroom, but come to rest on the playground."

As is the case with *detect*, the contributors to this issue do not, for the most part, address *elect* directly. However, some bring forward factors that would contribute strongly to a person *electing* to pursue a detected potential transfer. The expansive framing of teaching/learning advocated by Engle et al. (2012/*this issue*) would make what is learned much more meaningful in a broad range of circumstances and therefore more meriting of attention. The same can be said for teaching/learning that fosters seeing deeper structures (Chi & VanLehn, 2012/*this issue*). Richland et al. (2012/*this issue*) emphasize the problem of meaninglessness in students' typical learning of basic mathematics. The authors discuss how students end up viewing mathematics as a bundle of rituals to be executed accurately, with little sense of mathematical or practical significance. One consequence is misapplications when students are asked directly to address one or another kind of problem. Another consequence would be reluctance to *elect* mathematical approaches to understanding situations.

Schwartz et al. (2012/*this issue*) mention work by Chase, the second author, on 8th graders learning about genetics from a collection of games in different rooms highlighting different aspects of genetics. Chase found that the simple measure of leaving-after-failure accounted for 50% of the variance in learning. The quitters tended not to learn: Disengagement naturally subverted learning opportunities, including connecting previous learning to the present moment. Schwartz et al. (2012/*this issue*) relate this to Dweck's (1975, 2000) entity learner phenomenon, where learners hold "either you get it or you don't" belief systems that undercut investment of effort.

These perspectives speak strongly to making learning meaningful and fostering productive persistence. However, they say little about the problem of previously ingrained responses and other motives hijacking the desired transfer. Rehearsal techniques with reflection are one way of coping with this, as for instance found in programs and studies designed to help students manage their anger and sexual impulses (e.g., Reyna, Adam, Poirier, LeCroy, & Brainerd, 2005).

## ARE WE READY TO TEACH FOR TRANSFER?

Conditions for transfer have been in the foreground so far: When does transfer of learning happen, when not, and why?

815 The contributors to this collection have explored these questions richly but certainly have not stopped there. Educators as well as researchers, they all have discussed not just what's going on but how we can do better. Their recommendations are diverse, and some appear at various points earlier. However, it may be useful here to bring forward broad theories of action from each of the articles.

Chi and VanLehn focus on the challenge of learners coming to see through the surface features of problems to their deeper parallels and differences. She advocates teaching for deeper understanding generally, with engaging learners in self-explanation as one important strategy. However, Chi and VanLehn also urge directly helping learners to read through those surfaces by examining first- and second-order interactions of surface features, from which deeper relationships can be discerned. Engle et al. find a villain in typical classroom patterns that telegraph to learners a narrow view of content as for now, this day, this unit—what they term *bounded framing*. The authors advocate expansive framing, which in various ways fosters expectations for diverse later uses, for the relevance of prior learnings to the current moment, and for the authorial role of the learners in making the most of their own learning.

Relatedly, Lobato champions an actor-centered perspective on learning for transfer. She warns about concluding that transfer has failed when learners do not soon manifest the rather broad and deep transfers desired by experts. She envisions a dynamic of teaching and learning attentive to and encouraging of the many kinds and layers of transfer that learners display. Richland et al. bewail the extremely superficial learning of mathematics. They outline a vision of mathematical learning that treats mathematical connections in an explicit public way and engages students in struggling to make sense of important mathematics. Certainly the same principles could be applied to any discipline.

850 Finally, Schwartz et al. build on their distinction between routine and adaptive transfer to recommend a course of learning that navigates between the tensions of routines and novelty. The “optimal adaptability corridor” would provide efficient tools for straightforward situations along with enough stretch to build flexible understandings generative of further learning. An important tool here is asking learners to explore and construct their own understandings of topics before exposure to standard explanations.

860 It's reasonable to ask whether these somewhat different recommendations conflict with one another. We think not! Besides many overlaps, the recommendations appear plainly complementary. The differences emanate from the particular challenges the authors put center stage. Of course, this does not mean that the authors would agree on every point. 865 However, for the most part one could bundle together their

various ideas toward a vision of teaching and learning far more attentive to transfer than the norm.

So, are we ready to teach for transfer? Perhaps not completely. There is still both the matter of the three bridges of detect, elect, and connect and relatedly the role of motivations and dispositions in transfer. Teaching for transfer ideally not only prepares the learner to figure out how what's been learned connects to new situations but also to detect the opportunities and elect to pursue them. Unfortunately, detect and elect pose major challenges of their own, even more so “in the wild,” away from focusing and motivating laboratory or classroom contexts.

As to detect, recall how the clutter of events in another context, comfort with the messages one is hearing even though they have flaws, or functional fixedness and mental set can mask potential transfers. Patterns of instruction that encourage reflective mindful processing (high-road processing as we called it before) *not just in the classroom but beyond* can be expected to increase rates of detection. Indeed, all the authors champion in one way or another the cause of motivated reflective mindful processing. Their visions of good learning seem likely to cultivate broad dispositional characteristics such as mindfulness (Langer, 1989), need for cognition (Cacioppo & Petty, 1982), need for validity more than quick cognitive closure (Kruglanski & Webster, 1996), and incremental versus entity stances toward intellectual challenge (Dweck, 1975, 2000).

As to elect, recall how strong rival habitual responses and urgent countermotives, or also total indifference to a theme, can preempt potential transfers. Intellectual understanding alone is not likely to save the day when such interference is involved. To add to previous examples, consider Zimbardo's (2006) students who abused their fellow students despite humane principles they must have held, or the observations of Darley and Latane (1968) about the indifference of bystanders who fail to apply simple principles of helping a person in need. Called for are patterns of instruction that change the emotional and motivational landscape through such means as reimagining scenarios, cultivating empathy, and role-playing, as for instance in some school programs addressing sexual behavior and school violence (e.g., Reyna et al., 2005). More broadly, Bereiter (1995) urged cultivating general dispositions that motivate transfer, mentioning moral dispositions such as respect for human life and thinking dispositions such as a scientific approach to natural phenomena.

So now, finally, are we ready to teach for transfer? If “we” means researchers, the research base to improve practice considerably certainly exists. However, is the rest of the world ready? For many teachers and students, knowledge of whatever sort is something to “possess,” to have in the mental warehouse ready for deployment as acquired. The key question for these teachers and their students becomes whether students can show knowledge on demand—through assignments and tests that relatively directly call for what

hopefully has been learned. Such settings of learning display what might be called a *learning culture of demand*.

Students can learn a great deal that way. A learning culture of demand can serve quite well when later contexts of use cue and motivate deploying what's been learned, thereby helping with detect and elect, and when applications are straightforward, making connect tractable. Recalling the familiar distinction between passive and active vocabulary, a culture of demand can build a passive "vocabulary" of skills, information, and understandings. Moreover, a culture of demand simplifies the logistics of education in ways reinforced by the current emphasis on high-stakes standardized exams. Exercises and tests can be relatively direct rather than open-ended. Courses and units can be relatively encapsulated rather than richly cross-connected—bounded rather than expansive framing in terms of Engle et al. (2012/this issue). Finally, notice that a culture of demand does not exclude some degree of learning for understanding. For instance, one can teach the law of supply and demand with plenty of interpretive exercises in response to varied problems.

However, for many of the roles educators envision for knowledge in learners' lives, a passive vocabulary is not enough. The environment does not strongly cue up the knowledge. Also, use is more discretionary and often in the face of contrary habits, intuitions, motives, and expectations from oneself or others. Most students participating in a straightforward unit on the law of supply and demand probably would not make spontaneous links later to love or the price of oranges. One needs to be motivated to do so or have a general mindful disposition to look for possible bridges.

What's needed rather than a learning culture of demand is a *learning culture of opportunity* with the expansive framing Engle et al. (2012/this issue) suggest. Such a culture would not constantly organize students' work as a series of highly targeted demands. It would often engage learners in farther ranging and more open-ended experiences where supports are "faded" over time. Learners would more often need to grope for potentially relevant prior knowledge (detect) and use judgment to decide on its relevance and how to proceed (elect). Such a culture would anticipate likely counterhabits and countermotivations undermining later opportunities and prepare learners to face them. Indeed, such a culture would not limit its activities strictly to the classroom, but reach beyond the walls, for instance, through reflective diary keeping about facets of everyday life or participation in social and intellectual initiatives in the home and community.

In summary, however well we understand the conditions of transfer technically, widescale attention to transfer of learning in education calls for a shift of mind-set about what it means to know something and the kind of learning culture that fosters that kind of knowing. But the good news is this: Typical education has difficulty with transfer of learning not because transfer is an occult mystery or because it is intractably difficult to attain. We just need to build the right

bridges . . . and build them in the right places, classrooms, and schools hither and yon. This sounds very much like a challenge of transferring teaching for transfer.

Q2

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