Domain-Specific Principles Affect Learning and Transfer in Children

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In this paper I discuss the curious lack of contact between developmental psychologists studying the principles of early learning and those concentrating on later learning in children, where predispositions to learn certain types of concepts are less readily discussed. Instead, there is tacit agreement that learning and transfer mechanisms are content-independent and age-dependent. I argue here that one cannot study learning and transfer in a vacuum and that children’s ability to learn is intimately dependent on what they are required to learn and the context in which they must learn it. Specifically, I argue that children learn and transfer readily, even in traditional laboratory settings, if they are required to extend their knowledge about causal mechanisms that they already understand. This point is illustrated in a series of studies with children from 1 to 3 years of age learning about simple mechanisms of physical causality (pushing-pulling, wetting, cutting, etc.). In addition, I document children’s difficulty learning about causally impossible events, such as pulling with strings that do not appear to make contact with the object they are pulling. Even young children transfer on the basis of deep structural principles rather than perceptual features when they have access to the requisite domain-specific knowledge. I argue that a search for causal explanations is the basis of broad understanding, of wide patterns of generalization, and of flexible transfer and creative inferential projections—in sum, the essential elements of meaningful learning.

In this paper I will consider the effects of principles that guide early learning, such as those described by Gelman (this issue), on later learning in children. This is not an easy task, as psychologists who have studied constraints,
biases, or guiding principles have looked primarily at very young children's naturally acquired knowledge. In contrast, those studying later learning have tended to concentrate on supposedly domain-independent mechanisms and the acquisition of knowledge that is essentially independent of domain-specific biases.

These differing emphases have led to some puzzling disparities concerning received views of young children's learning and what we believe to be true of older children. Specifically, we appear to grant a great deal more efficiency to the learning of infants than we do to that of older children. This could be because any influences of domain-specific biases to learn are over by, say, age five to seven and what one sees in older children is their gradual emergence as increasingly efficient all purpose learning machines, acquiring and using domain-general strategies that will enable them to learn almost anything by brute force. But it could also be the case that because the influence of domain-specific constraints has rarely been investigated in traditional learning experiments, children are granted less ability than they actually possess.

Unlike the other authors in this series, I come from just such a tradition, where the only "constraints" on learning were those resulting from some bottleneck in the information processing capacity of the system that many think is age-related, or to paucities in accrued knowledge (Brown, Bransford, Ferrara, & Campione, 1983). Keil, in his discussion of these papers, describes me as the most eclectic of the group, and I think this is a reflection of the tradition from which I originally addressed issues of learning. In this paper, I reconsider young children's learning and transfer in laboratory settings from the viewpoint of the potential influence of the kinds of theories, biases, or guiding principles that have been the main focus of the work of the others in this volume.

THE PROBLEM WITH TRANSFER: IDENTICAL ELEMENTS VS. CAUSAL PRINCIPLES

One of the problems of studies of learning and, particularly, transfer in children is the tendency to believe that this learning takes place in a kind of cognitive vacuum. Influenced by associative learning theories, most notably Thorndike's (1913), learning and transfer have been treated as processes that are content-independent and age-dependent. That is, in discussions of transfer precious little attention has been paid until recently to what is being learned. Indeed, Allport accused Thorndike and his contemporaries of studying "absurdly inconsequential tasks" (1937, p. 37), such as crossing out p's, then q's in texts and sorting shapes, then colors. It is not clear why one would expect retention and/or transfer of such "learning." In the developmental literature, it was assumed for a long time that transfer was age-
dependent, with young and not so bright children being regarded as particularly loath to transfer what they know. Both of these positions interact and stem from Thorndike's theory of identical elements.

Identical Elements
In their classic paper, Thorndike and Woodworth (1901) argued that one can expect transfer between two stimulus environments to the extent that they share "identical elements" in common. What an identical element would look like was in considerable dispute, then and now (Allport, 1937; Anderson, 1987; Brown, 1989; Lashley, 1929; Orata, 1945); and Thorndike himself was inconsistent on the matter (Thorndike, 1913 vs. Thorndike, 1926). But the term was generally taken to mean identical at the level of the surface features of the stimulus environment.

Perfectly respectable contemporaries of Thorndike took an alternative position on transfer: that one cannot expect transfer if there is nothing meaningful to transfer. When learning can be organized around a guiding principle, however, transfer is determined by the extent to which the learner understands that principle. Judd (1908) argued persuasively that transfer is determined by the extent to which the learner discerns the common underlying causal structure that two situations share. Empirically, Judd studied such things as 12-year-olds learning about the principle of refraction, and found considerable support for his position.

Traditionally, children have been regarded as extreme Thorndikians, that is, they are thought to be even less likely to transfer, and even more reliant on perceptual similarity to mediate the process, than are adults (Brown, 1989). They are called perceptually-bound, because they are unduly influenced by surface appearance. But if, as we now know, infants are sensitive to deeper relational properties of, for example, physical causality (Bailargeon, Spelke, & Wasserman, 1985; Gibson & Spelke, 1983; Leslie, 1984a; Spelke, 1983), and learn about such properties rather than more peripheral ones, why should older children have the opposite bias? At the very least, this seems like wasteful programming.

But are young children perceptually-bound? It is clearly true that children below seven have a tendency to respond on the basis of perceptual similarity on a variety of tasks such as analogy, classification, free association, free recall, metaphor, and word definitions (Gentner & Toupin, 1986; Mansfield, 1977; Vosniadou, 1987). In fact, few deny that physical similarity is important in triggering access to appropriate knowledge in young children, but it is important for adults too (Anderson, 1987; Gentner, 1989; Ross, 1989). The question is whether physical similarity is all-important for young children, that is, is it the case that they cannot transfer on any other basis? Until recently it has been difficult to answer this question, as younger children in studies of transfer often lack the conceptual knowledge necessary to
go beyond surface features. In the absence of the requisite knowledge, it is
difficult to imagine any basis of responding other than mere appearance,
whether one is an adult or a child. Reliance on surface similarity is indeed a
typical finding with novice adult learners too (Chi, Feltovich, & Glaser,

Perhaps young children, universal novices, with their impoverished
knowledge of the world, find themselves dependent on surface cues more
often than do adults (Brown & DeLoache, 1978). They know little in many
domains. What else can they do but fall back on surface commonalties?
However, when they do have knowledge about basic distinctions such as
animate and inanimate (R. Gelman, 1986) and natural versus material kind
(S. Gelman, 1988; S. Gelman & Markman, 1987), they are able to make
inductive projections to novel exemplars on the basis of what kind of thing
they are dealing with, in the absence of perceptual support, or even when
perceptual attributes are pitted against category membership.

**Causal Principles**

Let us now imagine that Thorndike lost, and Judd won, the battle in the
early part of the century. Judd claimed that a search for underlying simi-
larity at the level of causal structure mediated transfer. Note that his was
both a domain-specific and a domain-general argument (Keil, this issue).
Whereas a search for causal explanation (at least implicitly) may underlie
knowledge building in all domains, children cannot be responsive to causal
mechanisms unless they have the domain-specific knowledge in question.
As Bullock, R. Gelman, and Baillargeon (1982) point out, a child who does
not know that sound waves exert force would surely reject the notion that
Ella Fitzgerald's voice could cause a glass to break.

The contemporary theory of transfer that most strongly emphasizes
causal structure is Gentner's (1983) Structure-Mapping theory. This theory
describes a set of implicit rules by which people are said to interpret analogy,
treated as a mapping of knowledge from one domain (the base) to another
(the target). Predicates are mapped from the base to the target according to
the following rules: (a) the specific properties (surface features) of the ob-
jects in the base are discarded; (b) the relations among the objects in the
source are preserved; and (c) higher-order relations (relations among rela-
tions) are preserved at the expense of lower-order relations. This last rule is
the principle of "systematicity," and it is within this principle that causal
structure is emphasized. Connected systems of relations, such as causality,
are more likely to be transferred than are isolated predicates. So Gentner is
basically in agreement with Judd and disagrees with Thorndike. But, in her
developmental studies, Gentner seems to favor a version of the perceptually-
bound hypothesis, when she argues that children rely on attributes rather
than relations, and that systematicity "may make a somewhat later develop-
mental appearance" (Gentner & Toupin, 1986, p. 297).
In contrast, I believe that a sensitivity to systematicity guides learning at all ages if the learners have some insight into the causal mechanisms in question (Brown, 1989). For example, consider two examples used by Gentner. The first is the famous analogy between Rutherford's model of an atom and the solar system. In order to see the systematicity in this analogy, one would need to know about such properties as attractive force, revolves around, more massive than, and distance, which are all causally interrelated if one understands the notion of a central force system. This is an excellent example of the type of abstract knowledge acquired late, often only as the result of formal schooling.

In contrast, consider the example used by Gentner (1989) of a simple causal chain form of systematicity, for example,

\[
\text{CAUSE}[\text{PUSH}(b_i, b_j), \text{COLLIDE}(b_j, b_k)] \\
\text{CAUSE}[\text{PUSH}(t_i, t_j), \text{COLLIDE}(t_j, t_k)]
\]

Seeing the common causal structure of push/collide in two scenarios where different objects are acting is, presumably, a very simple case of systematicity. Given the evidence of infants' precocity concerning the nature of objects and what makes them move (Buhler, 1930; R. Gelman & Brown, 1986; Gibson & Spelke, 1983; Leslie, 1984a, 1984b; Spelke, 1983), one might expect very early reliance on systematic relations in guiding transfer here. Actually, whether children transfer on the basis of attributes or lower level relations, or are sensitive to higher level causal relations, might be an excellent indication of their depth of understanding within a domain, rather than indicative of their developmental status per se.

**TRANSFER IN PRIVILEGED DOMAINS**

In order to consider the issue of whether children younger than Judd's 12-year-olds will transfer on the basis of deep structural principles rather than perceptual features, we need to consider the type of causal principles to which younger children may resonate. By positing a system of constraints on human learning one can begin to explain the puzzling disparity, from a strictly associationist point of view, between what infants can pick up perceptually and what they "choose" to learn about. For example, we know that infants are sensitive to the colors and forms of objects in that they dishabituate to changes along these dimensions (Cohen & Younger, 1983). Furthermore, infants categorically perceive color in much the same way that adults do; but color is not a feature readily learned about by infants and this early sensitivity to color is not followed by rapid learning about color words. Indeed, color terms are learned late and with considerable difficulty (Bornstein, 1985).

In contrast, young infants appear to learn rapidly about objects and people, not surface attributes of objects and people, but something much
more akin to “essences” (Medin & Ortony, 1989), such as what makes them move. Young children show early understanding that animate objects can move themselves and hence obey what R. Gelman (this issue) calls the innards principle of mechanism; in contrast, inanimate objects obey the external-agent principle; they cannot move themselves, but must be propelled into action by an external force.

If infants preferentially attend to an object’s pattern of motion (Bertenthal, Profitt, Spetner, & Thomas, 1985; R. Gelman, this issue), their initial cut on the world would make them learn rapidly that inanimate objects need to be pushed, pulled, or propelled into movement, whereas animate objects do not. Gelman (this issue) discusses early sensitivity to animate movement. And infants do seem to know a great deal about the properties of inanimate objects as well (Baillargeon, Spelke, & Wasserman, 1985; Gibson & Spelke, 1983; Spelke, this issue). Object perception in infancy appears to be guided by a coherent set of conceptions about the physical world: that objects cannot act on each other at a distance; that an object cannot pass through the space occupied by another; that movement must be externally caused; that once set in motion, the path of motion has certain predictable properties, and so on (see Spelke, this issue).

In brief, there are three essential interrelated parts to a structural constraints theory that could have important implications for how a child learns and transfers information about novel objects. Fundamental to learning is a search for cause, for determinism, and mechanism. Children assume (implicitly) that events are caused, and it is their job to uncover potential mechanisms. Second, that which determines an event and delimits potential mechanisms is different for animate and inanimate objects. Third, these initial biases determine, or at least constrain, what is selected from the range of available perceptual inputs to form the basis of emergent categories. Of the many sensations that children are sensitive to, they learn most rapidly about those constrained by core concepts (Medin & Ortony, 1989), guiding skeletal principles (R. Gelman, 1986, this issue), or theories of the world (Carey, 1985). Let us turn now to a discussion of children learning and transferring in traditional laboratory settings but under circumstances where there is a possibility that the influence of such guiding principles could be detected.

TOOLS AS MEANS FOR BRINGING

In an ongoing series of studies (Brown, 1986, 1987; Brown & Slattery, 1987) my colleagues and I have been looking at children’s understanding of the need for a point of contact if inanimate objects are to be propelled into motion. Specifically, we have been working on the learning and transfer of the “pull” and “push” schemas. There were three main reasons why we
chose to look at tools that afford certain relationships involving point of contact. First, infants are sensitive to the need for point of contact as early as seven months of age (Leslie, 1984a; 1984b). Second, one-year-old children show persistent self-motivated learning, mastering the function of such tools as sticks and strings as "means for bringing" (Piaget, 1952). Third, and in contrast, there exists an experimental data base that suggests abysmal learning and transfer in laboratory problem situations that demand the use of tools. The apparent contrast between early sensitivity and persistent self-motivated learning about tools reported in the infant and naturalistic studies and the seemingly dramatic lack of insight in laboratory transfer studies needs to be explained.

**Early Sensitivity**
First, let us consider infants' sensitivity to such causal mechanisms. Leslie (1984a, 1984b; Leslie & Keeble, 1987) showed 4- to 7-month-old infants scenarios in which a moving block travels toward a stationary block and is clearly seen to propel the stationary block into motion. In a second film, the moving block stops short of contact. In another example, a hand approaches a stationary doll and either appears to pick it up and move away, or it moves away in tandem but without physical contact, the doll apparently trailing behind. Using a habituation technique, Leslie demonstrated that infants are highly sensitive to such spatio-temporal discontinuities. They see the hand or the block as an agent to cause movement in an inanimate object. But the no contact scenarios are seen as anomalous events—magical violations of causal principles.

**Persistent Self-motivated Learning**
This early sensitivity is reflected in studies of 1-year-olds' exploratory play. By far the best descriptions of such self-motivated learning are Piaget's concerning his own children, who seem determined to master the functions of sticks, strings, and supports. By 12 months of age, his children clearly understood the need for a point of contact to bring inanimate objects into range. For example, Jacqueline (9 months) discovers that she can bring a toy within reach by pulling a blanket (support) on which it is placed. After failing to reach a toy duck, she grasps the blanket and the duck moves. "Seeing this, she immediately grabs the coverlet again and pulls it again until she can attain the objective directly—during the weeks that follow, she frequently utilizes this schema" (Piaget, 1952, p. 285). Lucienne (12 months), once having witnessed the action of the support, rapidly generalizes the schema to sheets, handkerchiefs, table cloths, pillows, boxes, books, and so on, she cannot be fooled by elaborate systems of overlapping pillows, drawing toward her only the particular pillow that acts as a support for the desired object. Once the baby understood the notion of the support, this knowledge
transferred rapidly to a variety of potential supports. The same is true of stick-like things (push schema) and string-like objects (pull schema), as "means for bringing" (Piaget, 1952, p. 295). Each new acquisition brings with it its own penumbra of generalization:

Let us note that once the new schema is acquired, it is applied from the outset to analogous situations. The behavior pattern of the string is without any difficulty applied to the watch chain. Thus, at each acquisition we fall back on the application of familiar means to new situations. (Piaget, 1952, p. 297)

Thus, Piaget believed in ready transfer in privileged domain.

It appears that young children actively seek out environments that support their exploration of domains they are currently trying to master, spontaneously generalizing across novel situations, rehearsing each acquisition until mastery (see also Karmiloff-Smith & Inhelder, 1974/1975). Piaget's delightful vignettes illustrate the child's:

(a) persistence;
(b) self-motivation, all Piaget does is leave stick-like things around;
(c) spontaneous error correction; and
(d) rapid transfer to all stick-like things or string-like things as tools for bringing; with
(e) all of the above focused on the particular mechanism the child is currently mastering.

When the support is mastered the child loses interest in it and concentrates next on the string, then the stick, and finally, the lever. A similar phenomenon has been reported in language learning with children spontaneously practicing and making repairs to newly emerging structures (Bowerman, 1982; Clark & Anderson, 1979).

LABORATORY TRANSFER STUDIES

I would like to argue that if (a) there is similarity at the level of causal structure and (b) the type of causality has been differentiated within the child's emergent theories of the world, then rapid learning and transfer would be expected. Thus, given the early sensitivity and spontaneous learning data, I would predict that there would be facile learning and transfer in laboratory situations if pulling or pushing were the underlying causal mechanism. But this is apparently not true, at least this position is not supported in an early series of laboratory transfer studies where sticks and strings were used (Alpert, 1928; Matheson, 1931; Sobel, 1939). The major claim from this database is that insightful learning or transfer does not exist below three years of age. But if infants are so fascinated by such tools in their spontaneous play, why can't they learn to solve problems that exploit this knowledge and interest? The contrast between the early sensitivity and persistent self-motivated
learning and the failure to learn in laboratory studies is, to say the least, puzzling.

Because of this puzzling disparity, I went back and considered the early transfer studies in some depth. The first major problem was that this research was done in the early days of experimental child psychology and the investigators were less than experienced with young children as experimental subjects. The majority of the studies were so closely modeled on Kohler's (1925) classic work with problem solving in apes that they could hardly be regarded as offering a hospitable environment for young children. For example, the children were required to retrieve objects with sticks, often through the bars of cages (cribs); and it did not seem to occur to anyone that a set of boxes more readily affords stacking and climbing to reach a desired object to apes than to less agile human toddlers! Furthermore, even though these early studies claimed to find no evidence of insightful learning and transfer below three years of age, the claim is not based on actual data. Below 30 months, the children are usually reported as "nonresponsive," or as "finding the tools themselves more motivating than the incentives" (Sobel, 1939) and thereby generating no data at all on the point of interest.

Second, and more crucial to my argument, is that the stimulus dimensions manipulated in these early studies were not relevant to pulling or pushing. Influenced as they were by Thorndike, rather than varying relevant attributes such as length or rigidity, they varied perceptual similarity of the learning and transfer tools. Variables, such as length or rigidity, that would influence a tool's affordance (Gibson & Spelke, 1983) as a means for bringing were not highlighted.

The Case of the Stick
To rectify these obvious problems, Anne Slattery and I designed a series of tool-use laboratory learning and transfer studies where we continued the tradition of manipulating perceptual similarity in the Thorndikian manner but where we also varied attributes relevant to the solution, that is, length, rigidity, and the degree to which the instrument "affords pulling or pushing." I will concentrate here on the highlights of a series of studies using only the pull schema.

In all studies the child and the mother sat side-by-side, the child restrained by a "sassy-seat" that effectively prevented reaching beyond arm's length. A desired moving, noise-making, toy (carousel, Mickey Mouse, etc.) was out of reach. In front of the child was a set of tools. The tools were at least 6 inches from making contact with the toy. In order to reach the toy, the child would need to select a "means for bringing."

In Figure 1 are some examples of possible tools. Set 1 contains examples of learning tools. Two of the tools in this set are appropriate for pulling: the long rake (1a) and the long hook (1d). All of the tools were painted an attractive red/white candy-cane color. The toy was set in motion and the child
told to "get that Mickey," or "get the butterflies" (on the carousel). If they did not do so unaided, the mother demonstrated the pull solution. After the child repeated the solution three times, she was given a set of transfer tools. A representative example is also shown in the bottom set in Figure 1. In two conditions there was at least one correct choice, that is, there was a tool long enough to reach, rigid, and with an effective head. The transfer set shown in Figure 1 has a correct solution, as the hook (2d) is long enough; it is also rigid and has an effective head. In two of the conditions no tool was "correct" because the rigid ones with an effective pulling head were too short. In each case, we scored which tool the child preferred to reach with. In the conditions with no correct tool, the experimenter hastily provided a long enough tool after the children were duped with too short tools. We chose
presented with either (a) the same problem again, (b) its mirror image, (c) the same problem with a different color string or toy and so on, in decreasing order of similarity. Or the children might receive the novel problem of that degree of difficulty, that is, problem 4. Again, these similarity variations had absolutely no influence on performance. What did influence performance was the ease with which the child could detect point of contact. Easy string problems (1 and 2) were unambiguous, and children as young as 14 months could solve these unaided. Harder strings (3–6) were more difficult, and the younger children (14–24 months) could solve them only as transfer problems. That is, if they were presented first, the children failed, but if they were demonstrated, or if they followed easy problems, the children learned, slowing down and making very deliberate head and eye movements as they traced the path of each string. Point of contact ambiguity, and this alone, influenced performance; similarity of toy, color of string, and even repetition of an identical problem did not affect learning efficiency.

Again there is the same problem in interpreting these data in terms of learning and transfer efficiency that there was with the tool use studies. Even though there was a clear gradient of difficulty, and learning did occur, the children's extreme sensitivity to the critical feature, the need for point of contact, left little room for learning and transfer. Because of this precocity, we were forced to thwart our subjects by testing them on even more difficult problems—trick string conditions (7 and 8 in Figure 4) that we invented for this purpose. Here the string that looks like it is attached, is not, while the string that looks like it isn't attached, is—after playing around unsuccessfully with magnets, we effected this trick by using microfilament, invisible wire used by fishermen. We pitted children's performance on plausibly possible and impossible versions of the same physical arrays (e.g., array 3, possible; 7, impossible; 4, possible; and 8, impossible in Figure 4). Before attacking the trick problems, children warmed up on easy problems, such as Problem 2 in Figure 4.

If children are truly indifferent to causal mechanisms, the possible and impossible arrays should be equally difficult; one would predict that children assigned to either condition would require the same number of reinforced trials to reach criterion. Such was obviously not the case. As can be seen in Table 2, 90% of children learned in one to two trials in the causally possible condition, whereas only a third learned at all in the impossible condition. Children below 24 months had special difficulty learning the solution to the impossible, no-contact string problems, only 17% reached criterion. If we consider the performance of only those children who did learn, almost all those in the possible condition learned in one trial, whereas it took five repetitions before the "impossible" problem was mastered. Of interest, too, is the children's reaction. The younger ones were clearly unhappy at the violation of their perfectly reasonable expectations that attached strings were
tool that was identical in color to the learning set (i.e., the candy-cane colored one). And they showed no preference for the physically similar hook (if hook was the original learning tool) over the physically dissimilar rake when given a choice. If the only potential puller was the right length (2d), it predominated. They learned rapidly that what was needed was a rigid tool with an effective pulling head of the correct length. Note that if there was a correct solution, it was a rare child who made a mistake. Children actively sought the appropriate tool; they were not distracted by physical similarity. Only in the conditions when there was no correct tool (because the ideal ones were too short) did a few children make a choice of a noneffective head, and that choice was always of a long rigid tool. On these no-choice trials, the children were visibly confused or upset, often claiming that the tool wasn’t big enough, either indirectly by leaving the field or directly by crying “I can’t reach, I can’t reach,” repeatedly. The most typical behavior was to finally choose the short tool with the effective head and try to wiggle out of the seat so they could reach.

Also interesting is what the children did with nonrigid tools. No one selected them as a tool of preference (i.e., the tool that they attempted to reach with). Thirteen children touched it first and instantly disregarded it, some even throwing it on the floor. They appeared to be quite sure that a tool for bringing must be rigid.

We decided to repeat the essential feature of this study but with fewer tools and a design that permitted us to pit the variables of interest systematically against each other. This enabled us to see which variables the children thought were most crucial for pulling. This second study was conducted in two phases, often over two successive days. The children were 24–42 months of age, slightly older because we needed several trials on the same child (between 12 and 18) which proved difficult to obtain from younger children.

The tools for the initial learning phase are shown in Figure 2. All children received tool set 1 first, the learning set, which tested for their tool of choice. All tools were rigid and were long enough to reach, but only two had effective pulling heads. Again, there was an age difference in the prevalence of unassisted correct choices (hook or rake), with children below 30 months (approximately) needing help, and those above this benchmark, performing unaided. It appears that the younger children needed to know the rules of this particular laboratory game because once seen, they selected appropriate tools, concentrating on those that would be most effective, although the younger ones sometimes had difficulty physically manipulating the tools and, therefore, needed help completing the reach. There were no noticeable differences in the subsequent performance either due to age or the need for assistance during original learning.

After three trials with the original tool of choice (hook or rake), the children were given tool sets 2–4 in random order. Shown in Figure 2 are the
Figure 2. Representative examples used in the learning phase of study 2.

set-ups only for children showing a hook preference (46%). Children with a rake preference received the same displays except that the rake was manipulated in the same manner as the hook. On tool set 2 the preferred tool (hook) was present, but it was not rigid, the only possible solution was to choose the nonpreferred tool (rake); 92% of children made the logical switch. On tool set 3 there are two preferred hooks, only one rigid; all reject the nonrigid tool. On tool set 4 there is no correct tool, the hook is nonrigid and the rake too short. Again the children showed distress, or questioned the appropriateness of the tools. Those who attempted retrieval unanimously chose the
Figure 3. Representative examples of the problems used in the variable preference stage of study 2.

short rigid tool. The remaining two sets (5 and 6) are identical to original learning with the exception of color of tool which appears to have no effect whatsoever, 62% of the children favor tools of original learning, the remaining switch to the other effective tool regardless of color.

Willing children (60%) then entered the second phase of the study where they received the tool sets shown in Figure 3 in random order with the exception that one-sixth of the sample received each of the six sets first. The sets shown in Figure 3 are for hook preference subjects only, similar sets were constructed for rake preference children. In set 1 we tested for length preference pitting a long and short preferred tool against each other. In set 2 we tested for rigidity, presenting a rigid versus nonrigid tool of preference. In set 3 both effective tools are available to test for preference of hook or rake. In set 4 we looked at color preference with the original learning candy cane color pitted against a novel color. Set 5 forces the observant child to choose
the nonpreferred correct tool. Finally, in a variety of set 6 scenarios there is no correct choice, for example, one preferred tool is too short, one is nonrigid.

To cut a long story short the data are unequivocal. Tool choice was predictable on the basis of the variables that afford pulling. The children were totally indifferent to color and relatively indifferent to the shape of the effective head, there being a 60–40 preference for original choices (e.g., rake over hook or vice versa). They were affected, however, by length, rigidity, and effective pulling heads. When forced to choose one over another, rigidity was always the dominant force, followed by effective pulling head, followed by length. That length was least important to these children may have something to do with the fact that they attempted to climb out of the chair on trials with too short tools. It is also a more difficult judgment call for older children—how long is long enough? In contrast they rarely attempted a retrieval with nonrigid tools which were generally regarded with contempt, "It's too squiggley." Older children who could talk summed things up quite well. For example, H (35 months) told us, "This one is too small, this one's to mop the floor, and this one's too (hits the nonrigid head back and forth with a look of contempt), I need a big strong one." And A (24 months), said, "This one is broken (nonrigid), want that one." Several children reacted to the no correct tool condition verbally, complaining, "Can't get it cause it's too far, can't get it, can't get it" (S, 30 months). Others pointed to previous set ups (on trays behind them) saying "That one," "I need that big one," (J, 27 months), or "I think that one's best" (J, 36 months).

In short, the children were not affected by color or the specific arrangements of tools on a tray. They were also indifferent to the particular effective head (rake vs. hook); both were fine for pulling even though the slight tendency to maintain preference would indicate a certain dependence on physical similarity to mediate transfer, one hook looks more like another than a rake. Only the variables that afforded pulling influenced performance; tools must be long enough, have heads with clear pull potential and be rigid. Nonrigid tools were particularly disdained.

Although interpretation of these data in terms of children's sensitivity to features that afford pulling are unproblematic, it is less clear what we can say about learning and transfer facility. One could argue that these studies were not measuring learning and transfer in the traditional sense because children all "transferred" immediately and, indeed, the older children showed one-trial learning. Provided with a long, rigid, object that affords reaching, children readily apply their knowledge to the novel setting. Even for the younger children, who did require the mother to demonstrate the choice, it could be argued that they needed only a few hints to learn the "rules of the game" before they could reveal their underlying competence.

The problem is that if one finds ready generalization to a variety of "stick-like" things as Piaget reports, is this because the novel situations are too
similar to the old to be a fair test of transfer? Or is it the case that once real understanding of the schema is reached, transfer is hardly an issue. As Piaget argues, transfer is the measure of true understanding.

In the case of laboratory studies like the ones discussed here, it is important to note the startling difference in efficiency when children are asked to learn about reasonable things, such as the effectiveness of a tool as an object of pulling, than when they are asked to discriminate pulling objects on the basis of color, texture, and so on. When we capitalize on their emergent knowledge of physical mechanisms, we can see how well children learn, whereas previously we saw only a pattern of inefficiency when they were learning about irrelevant features.

Children in these studies show what might be called intelligent situated learning (Brown, Collins, & Duguid, 1989; Greeno, 1988) in that the design of the tool itself lessens the cognitive load on the child. In our task the goal is separated from potential agents of pulling. The child is required to "see" the potential connection between the tool and the goal (Kohler, 1925). As such, the task requires "anticipatory imagery" (Piaget & Inhelder, 1969) whereby the child envisions the future pulling act. Faced with a tool that invites or affords pulling, the envisioning act required of the child is lessened. Faced with less hospitable tools, the envisioning act is more demanding.

There is an interesting developmental trend associated with the expression of intelligent situated activity. Recall that infants as young as seven months of age are sensitive to the need for a point of contact for pushing if habituation is used as the behavioral index of understanding (Leslie, 1984a, 1984b). Our data suggest that it is not until approximately 24 months of age that children immediately select the correct pulling tools on learning trials. What happens in between is very interesting. Bates, Carlson-Luden, and Bretherton (1980) provides evidence of tool use in the missing period. They examined ten-month-old infants attempting to reach a toy via a variety of tool use solutions, including supports, strings, hoops, hooks, and straight sticks. The variable of interest here is that the conditions could be divided into three types:

1. Unbreakable contact, where the tool and toy were physically attached, for example, the string was attached to the toy;
2. Breakable contact, where the tool was attached to the toy but could become unattached if moved, for example, the hook was around the toy and touching it but not physically inseparable; and
3. No contact, where the tool (stick and hook) did not touch the toy, the point of contact needed to be imagined, as in the Brown and Slattery studies.

The data are unequivocal. Ten-month-old infants performed extremely well when faced with unbreakable attached supports and strings and were
quite successful with the breakable contact situations involving hoops and hooks that were perceptually in contact with the toy in a suitable pull alignment. But they performed less well in the No Contact conditions involving a hook and a stick, in which the child must imagine the point of contact. In fact, if one looks closely at the scoring systems used in the No Contact condition, the infants showed little understanding of the pull schema. They are described as either playing with the tool for its own sake, waving the tool in the direction of the goal, or accidentally brushing the goal with the tool while not looking at the goal. Further support for their lack of insight is the fact that they find the hook (with an effective head) no more helpful than the stick, unlike the 18-month-old children in the Brown and Slattery studies.

Combining the Bates et al. work and the Brown and Slattery studies, we can paint an interesting developmental scenario. Although children in habituation paradigms seem to understand the need for point of contact early (5–7 months), they cannot apply that knowledge to tool use tasks at 10 months unless the contact between the tool and the goal is provided in the physical layout of the task itself, that is, the solution is physically situated, if you will, in the environment itself. Several months later, the younger children in the Brown and Slattery studies (13–18 months) can learn, with a demonstration, to envision the point of contact that is not specified in the visual array but is invited by the pulling features afforded by the tools. By 24 months children readily note the pulling potential of unattached tools. Although young children "have" the requisite knowledge very early on, they need help in the form of a demonstration, or pulling specific cues provided by the environment, to prompt the application of their knowledge. As they mature, they need less environmental support and can imagine pulling functions not demonstrated or physically specified in the environment. Finally, at about three years of age, children begin to perform less competently in terms of our scoring standards simply because any long rigid tool (even the stick or mop) can be used to bring objects into range if one has the planning skills and physical dexterity to use them to knock an object from side to side until it can be reached. A supportive environment helps the early expression of understanding, but this is not needed by older children who can engage in anticipatory imagery of future activities, an ability that Piaget would place in Stage VI of the sensori-motor period (18–24 months).

The Case of the String
Brown and Slattery also looked at the string as a means for pulling because there appears to be a significant developmental gap between the ability to solve support and string problems, at about 10–12 months (Uzgiris & Hunt, 1975; Willits, 1984), and the ability to solve stick problems, often not achieved until 18 months. Using strings as "means for pulling" would, we
thought, allow us to look at children's emergent understanding at a still younger age. We selected more difficult string problems than Bates et al. (1980), ones that involved a choice between several available strings, only one of which made contact with the goal. Children between 14 and 36 months were given the problems shown in Figure 4 (loosely adapted from Richardson, 1932). Attached to the end of a colored string was a squeezable squeaky toy (big bird, raccoon, elephant, etc.). Three physical attributes were manipulated—color of string, identity/difference of lure animals across trials, and the physical configuration of the problem. For example, children who had just learned a hard string problem of type 3 (in Figure 4) would be
presented with either (a) the same problem again, (b) its mirror image, (c) the same problem with a different color string or toy and so on, in decreasing order of similarity. Or the children might receive the novel problem of that degree of difficulty, that is, problem 4. Again, these similarity variations had absolutely no influence on performance. What did influence performance was the ease with which the child could detect point of contact. Easy string problems (1 and 2) were unambiguous, and children as young as 14 months could solve these unaided. Harder strings (3–6) were more difficult, and the younger children (14–24 months) could solve them only as transfer problems. That is, if they were presented first, the children failed, but if they were demonstrated, or if they followed easy problems, the children learned, slowing down and making very deliberate head and eye movements as they traced the path of each string. Point of contact ambiguity, and this alone, influenced performance; similarity of toy, color of string, and even repetition of an identical problem did not affect learning efficiency.

Again there is the same problem in interpreting these data in terms of learning and transfer efficiency that there was with the tool use studies. Even though there was a clear gradient of difficulty, and learning did occur, the children's extreme sensitivity to the critical feature, the need for point of contact, left little room for learning and transfer. Because of this precocity, we were forced to thwart our subjects by testing them on even more difficult problems—trick string conditions (7 and 8 in Figure 4) that we invented for this purpose. Here the string that looks like it is attached, is not, while the string that looks like it isn't attached, is—after playing around unsuccessfully with magnets, we effected this trick by using microfilament, invisible wire used by fishermen. We pitted children's performance on plausibly possible and impossible versions of the same physical arrays (e.g., array 3, possible; 7, impossible; 4, possible; and 8, impossible in Figure 4). Before attacking the trick problems, children warmed up on easy problems, such as Problem 2 in Figure 4.

If children are truly indifferent to causal mechanisms, the possible and impossible arrays should be equally difficult; one would predict that children assigned to either condition would require the same number of reinforced trials to reach criterion. Such was obviously not the case. As can be seen in Table 2, 90% of children learned in one to two trials in the causally possible condition, whereas only a third learned at all in the impossible condition. Children below 24 months had special difficulty learning the solution to the impossible, no-contact string problems, only 17% reached criterion. If we consider the performance of only those children who did learn, almost all those in the possible condition learned in one trial, whereas it took five repetitions before the "impossible" problem was mastered. Of interest, too, is the children's reaction. The younger ones were clearly unhappy at the violation of their perfectly reasonable expectations that attached strings were
TABLE 2
Trick String Condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Causally Possible</th>
<th>Causally Impossible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age in Months</td>
<td>Percent Learners</td>
<td></td>
</tr>
<tr>
<td>14-24</td>
<td>83</td>
<td>17</td>
</tr>
<tr>
<td>24-36</td>
<td>97</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trials to Criterion (max=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(learners only)</td>
</tr>
<tr>
<td>14-24</td>
</tr>
<tr>
<td>24-36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-24</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>24-36</td>
</tr>
</tbody>
</table>

the correct pulling tool. Many refused to continue; some tried to leave the field by getting out of the sassy seat, others showed evident signs of discomfort—crying, fussing, or regressing to reaching, mindless trial and error, or brute force—trying to move the board on which the problem was displayed. While some older children showed distress, more showed surprise and curiosity, smiling and laughing. They even talked about being tricked (“You tricked me, huh?”). A few refused to continue, and some developed interesting strategies that they did not relinquish even when they were subsequently given causally possible trials. For example, they pulled two strings together, or gave little tugs to all strings before committing to a choice. When given the chance at the end of the session, the older children investigated the trick string avidly, running their fingers over the invisible string with evident surprise and pleasure at discovering the trick explanation.

Again one can see the important influence on children’s learning exercised by domain-specific biases. Children understand the pulling function of attached strings as young as 10 months of age (Bates et al., 1980). By 14 months of age they are barely distracted by more difficult problems that offer them a choice of strings; they merely slow down and examine the array carefully, searching for the appropriate connecting string. These biases are so strong
that the children are distressed by an event that violates their expectation. They experience difficulty learning to pull a seemingly no-contact string. At a slightly older age, they are fascinated by this trick and try to discover how it was arranged. This developmental pattern is similar to that found with the tools. As children mature, less and less environmental support is needed to elicit the application of their knowledge. Biases to look for point of contact in moving inanimate objects cause them to show early competence in simple arrays (Bates et al., 1980), careful, deliberate search of confusing arrays (such as arrays 3–6 of Figure 4), and impaired learning of solutions that violate their emergent theory of what could cause the movement of inanimate objects.

I conclude that young children do show rapid insightful learning and transfer if they are familiar with the mechanism of causality that underlies the deep structural similarity between problems. If we are dealing with such privileged domains, transfer is not an issue, it can be assumed. Even one-year-olds can override surface features of physical similarity and respond in terms of causal relations if they know what kind of thing it is that they are dealing with—if they understand the causal mechanism in question.

PREFERRED DOMAINS AND LATER TRANSFER

These findings of early learning and transfer would appear to jar with the commonly reported finding that transfer rarely happens in children’s laboratory learning unless mediated by physical similarity (Brown, 1989; Brown & Campione, 1984; Brown, Kane, & Long, 1989). However a closer look at some recent studies offers a reconciliation. The most popular method of studying transfer in recent studies is modelled after Gick and Holyoak’s (1980) story format. A story problem, such as Duncker’s (1945) ray and tumor problem, is followed immediately by another problem that shares the same underlying structure and solution but differs in surface format. This technique has been used with children and, they, like adults, rarely note the commonality (Brown, 1989).

In a recent series of studies Mary Jo Kane and I (Brown & Kane, 1988) used the same story format, but the relations embedded in the stories were meaningful to the children, as they were based on either (a) simple acts of physical causality, such as pulling, pushing, swinging, stacking, and so on; or (b) novel mechanisms that were particularly interesting for the children, that is, animal defense mechanisms, such as camouflage, mimicry, warning coloration, and so on.

Under these circumstances, children as young as 3–4 years of age transferred solutions to novel problems even in the Gick and Holyoak paradigm. Children can solve problem analogies if the relations to be transferred are either based on simple principles of physical causality (push, pull, etc.).
Furthermore, transfer is readily obtained even when the relations are not rooted in experience but are such that children's attention is clearly captured by interesting common mechanisms of defense. One cannot study learning and transfer in a vacuum, transfer propensity will be strongly influenced by that which is to be learned.

This point is made again in another paradigm referred to as classical analogies (Goswami, 1989; Goswami & Brown, in press). It has been claimed that before the period of formal operations, children cannot solve classical analogies of the form A:B::C:D and theorists as diverse as Piaget (Piaget, Montangero, & Billeter, 1977) and Sternberg (Sternberg & Nigro, 1980) concur. Yet a review of the literature reveals the same disturbing problem as in the analogical transfer literature—one could just as well argue that the subjects do not possess the causal knowledge necessary to solve the problems rather than that they suffer from an across the board failure to reason adequately about higher order relations (e.g., "automobile is related to gas as sailboat is to—travel/wind/sails/rudder). Causal relations such as "powered by," "habitat," and so on predominate in these problems and we have no means of knowing if children understand them.

To bypass this problem Usha Goswami and I (Goswami & Brown, in press) gave 3-6-year-old children classic analogies based on causal relations. We had reason to believe that they understood actions such as cutting, wetting, and so on (Brown & French, 1976; Bullock, Gelman, & Baillargeon, 1982; Das Gupta & Bryant, 1989). We included a causal reasoning control to ensure that we knew which actions they were familiar with. The problems were of the form—whole lemon:single slice of lemon::whole loaf of bread:/(d) slice of bread/(e) slice of cake/(f) squeezed lemon half/(g) yellow balloon/(h) orange. The correct choice was (d), the correct transformation and the correct object. The distractors were: (e) correct causal change, wrong object; (f) correct object, wrong transformation; (g) mere appearance match; and (h) a category match. Again, the findings were clear: 4-6-year-olds who knew all of the causal relations performed extremely well (approximately 94% and 98% passed criterion). Classical analogies are clearly no problem for children when they have the domain-specific knowledge of the particular causal agent in question. Three-year-olds' performance on the analogies was predicted by their knowledge of the causal agents, which was imperfect. Forty-three percent solved the causal knowledge questions and 38% the analogies. If they knew the cause, they almost always solved the analogy correctly. We replicated these results when the analogies involved thematic categories (Goswami & Brown, in press), again an area of knowledge children learn about early and prefer as a basis of categorization (Bauer & Mandler, 1989; Markman & Hutchinson, 1984; Nelson, 1974; Smiley & Brown, 1979).

In summary, I believe it is a mistake to continue to regard transfer as age-dependent and content-independent. Children are just as likely to transfer as adults if what they are required to learn is embedded in a causal nexus
they have differentiated. It appears that principles of physical causality, for example, guide initial attention and enable the learning of novel problems that are based on this evolving knowledge.

CONCLUSION

I would like to argue that the child's spontaneous search for causal explanation is the basis of broad understanding. Wide patterns of generalization, flexible transfer, and creative inferential projections are all indices of deeper understanding of causal mechanism. Causal knowledge works to make certain patterns of correlated properties more relevant than others and provides a rationale for their interrelationship (Johnson-Laird, Hermann, & Chaffin, 1984; Wattenmaker, Nakamura, & Medin, 1988). Children can and do learn on the basis of relational properties if they have the requisite causal knowledge. Their apparent predilection to operate as if surface features were important is the result of three factors. First, they often are important. As Medin and Ortony (1989) point out, surface features are often constrained by deeper structural meanings and children are sensitive to just these kinds of correlated similarities that lead to the deeper and central properties (S. Gelman & Markman, 1987). Second, because of these correlated relations, sensitivity to surface features has a high probability of paying off; noting stable similarities among the surface properties might act as a crutch to new learning while the child is differentiating the core structures within her emergent theories. Third, for young children, and novices who have not yet differentiated the deeper structure, appearance matches serve as a fall-back option when theory fails.

Dependence on surface similarities is fallible, however, as all surface similarities do not correlate with deep structure; appearances, as in the case of whales and fishes, can be misleading. If the child is captured by superficial features that are not rooted in a stable causal explanation, learning should be fleeting and fragile. The traditional pattern of laboratory transfer suggests that it is just such momentary partial understandings that are captured. Rapid, transitory judgments in the absence of causal explanation are not the basis for sustained learning or conceptual change.

In contrast, when learning is in a domain where the child has differentiated the underlying causal structure, then it takes on a very different complexion. Characteristic of such learning is:

(a) Relative ease. For example, two-year-olds learned the causally possible string problems much more readily than the superficially similar but causally impossible event (see also Baillargeon, R. Gelman, Meck, Massey, & Graber, 1989);
(b) Persistent, self-motivated learning (Piaget, 1952);
(c) **Goal-directed spontaneous error correction and rehearsal** (DeLoache, Sugarman, & Brown, 1985; Karmiloff-Smith & Inhelder, 1974/75; Piaget, 1952);

(d) **Insightful learning** (Kohler, 1925), rather than trial and error; and

(e) **Broad rapid transfer** that is not necessarily dependent on surface similarity, but is guided by deeper relational structure (Brown, 1989).

Broad application of knowledge is particularly likely if there is similarity across problems at the level of causal structure and if the type of causal mechanism has been differentiated within the child’s emergent theories of the world. Children come endowed with predispositions to learn about certain privileged classes of information. These biases serve to constrain attention and guide learning (R. Gelman, this issue). The child is sensitive to, and actively seeks out, just those environments that feed these biases. This tendency makes learning and transfers easier, even possible. But note we still need a learning theory. The child may come endowed with predispositions to learn about certain kinds of things over others. But she still has to learn about them; note the gradual perfection of the pull schema between the ages of 10 and 36 months. And, we should not forget that by seven or eight years of age, human beings are starting to be fairly efficient general purpose learning machines too (Brown et al., 1983). With experience, the child becomes able to learn almost anything by brute force, that is, will, effort, skill, and strategies. It just so happens that in the early years the child does not have to work so hard to acquire the fundamentals.

We conclude that even young children show insightful learning and transfer on the basis of deep structural principles, rather than mere reliance on salient perceptual features, when they have access to the requisite domain-specific knowledge to mediate that learning. They show impressive early understanding about the need for a point of contact between a tool and an inanimate object if that object is to be brought into range. Early expression of this knowledge is assisted if part of the problem solution is situated in the problem array itself (e.g., the tool is in physical contact with the goal). Gradually, they can solve more difficult problems where they must anticipate the effects of bringing the tool into contact with the desired object, but again this is greatly assisted by the provision of tools whose critical features afford pulling (length, rigidity, or effective head). Finally, they can adapt almost any long rigid tool creatively and even solve causally impossible string problems that they recognize as tricks.

Young children’s predispositions to learn about certain classes of events is displayed in early sensitivity to critical cues and systematic exploratory learning of increasing complex applications of that knowledge. The predispositions bias and assist certain classes of learning, but the child still needs to learn to apply this knowledge with increasing finesse and flexibility.
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