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Mapping the mind

Domain specificity in cognition and culture

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7 Domain-specific knowledge and conceptual change

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Overview

We argue that human reasoning is guided by a collection of innate domain-specific systems of knowledge. Each system is characterized by a set of core principles that define the entities covered by the domain and support reasoning about those entities. Learning, on this view, consists of an enrichment of the core principles, plus their entrenchment, along with the entrenchment of the ontology they determine. In these domains, then, we would expect cross-cultural universality: cognitive universals akin to language universals.

However, there is one crucial disanalogy to language. The history of science and mathematics demonstrates that conceptual change in cognitive domains is both possible and actual. Conceptual change involves overriding core principles, creating new principles, and creating new ontological types. We sketch one potential mechanism underlying conceptual change and motivate a central empirical problem for cognitive anthropology: To what extent is there cross-cultural universality in the domains covered by innate systems of knowledge?

Domain-specific cognition

The notion of domain-specific cognition to be pursued here is articulated most clearly by Chomsky (1980a). Humans are endowed with domain-specific systems of knowledge such as knowledge of language, knowledge of physical objects, and knowledge of number. Each system of knowledge applies to a distinct set of entities and phenomena. For example, knowledge of language applies to sentences and their constituents; knowledge of physical objects applies to macroscopic material bodies and their behavior; knowledge of number applies to sets and to mathematical operations such as addition. More deeply, each system of knowledge is organized around a distinct body of core principles. For language, these are the principles of universal grammar;

for physical objects, the principles might include Newton's axioms and the principles of continuity and solidity; for number, they might include the principles of one–one correspondence and succession.

This notion of domain specificity provides a basis for determining, and distinguishing among, the domains of human knowledge: Two systems of knowledge are distinct just in case they center on distinct principles. For example, if knowledge of language and knowledge of number were found to center on the same core principles, psychologists should conclude that they constitute a single system of knowledge, despite the many obvious differences between the abilities that knowledge of language and knowledge of number support. Indeed, Chomsky (1980b) has suggested that language and number are connected in this way. This notion similarly provides a basis for distinguishing the genuine cognitive domains from more trivial collections of beliefs: Only genuine domains are characterized by distinct sets of core principles. In particular, reasoning about material bodies, about persons, and about sets may well depend on distinct systems of knowledge of physics, psychology, and number. In contrast, reasoning about billiard balls, about bricks, and about plates probably depends on a single knowledge system: The core principles underlying reasoning about one of these collections of objects probably apply to the other collections as well (Carey, 1985).

Domain-specific perception

If human reasoning depends on domain-specific knowledge systems, then reasoners face a crucial task: They must single out the entities to which each system of knowledge applies. For example, a well-developed system of knowledge of psychology is useless unless a reasoner can determine when he or she is faced with a person. Similarly, systems of knowledge of physics and number can function only insofar as a reasoner can single out material bodies and sets. The mechanisms that single out such entities need not be (and never are) flawless: It is sufficient for the reasoner to pick out some of the persons, some of the material bodies, and the like. Without some mechanisms for singling out entities within a domain, however, reasoning cannot proceed. A domain-specific reasoner cannot simply ask of some part of the layout, "How does this thing behave?" The reasoner also must ask, "What kind of thing is this?" (see Wiggins, 1980).

We will call the processes that single out material bodies, persons, and sets *domain-specific perception*. These processes may not be perceptual, however, in a narrow sense. Most of the processes studied in psychophysics, sensory physiology, and computational vision do not function to single out the entities about which one reasons but rather they function to construct representations of the continuous surrounding surface layout. Vision, for example, appears to culminate in representations of the distances, orientations, colors, textures, and motions of light-reflecting surfaces (Gibson, 1950; Marr, 1982).

These representations are not sufficient for the operation of domain-specific reasoning. To reason about material bodies, one must carve the surface layout into unitary, bounded, and persisting things (Spelke, 1988). To reason about number, one must represent a collection of bodies, surfaces, or other entities as a set (Gelman & Gallistel, 1978; also see Shipley & Shepperson, 1990; Wynn, 1992). To reason about human action and mental life, one must represent a portion of the surface layout as a sentient, purposive being. The processes that culminate in such representations are our focus here.

There are two general ways in which the task of apprehending the entities in a domain could be accomplished: Domain-specific perception either could depend on principles that are distinct from the principles guiding domain-specific reasoning, or domain-specific perception and reasoning could depend on a single set of principles. Consider, for example, the domain of reasoning about human action and experience. It is possible that perceivers single out human beings by virtue of a face-recognizer, a voice-recognizer, a gait-recognizer, and the like. Whenever the perceiver is confronted by eyes, hair, and other features in the proper configuration, his or her face-recognizer would signal the presence of a person. This signal would then trigger the operation of the processes of psychological reasoning, whereby the actions of the person are understood in terms of the person's goals and feelings. On this view, apprehending persons and reasoning about human actions depends on distinct principles: principles governing the physical arrangement of eyes, noses, and so forth, on one hand, and principles concerning the relation among purposes, perceptions, and the like, on the other. Psychological reasoning would proceed appropriately, because the mechanisms that embody these distinct principles would be suitably linked together.

Alternatively, perceivers may single out persons by analyzing the behavior of entities, asking whether an entity's behavior appears to be directed to some goal, to be guided by perceptions of its environment, to be colored by emotions, and so on. Entities would be perceived as persons insofar as their behavior was consistent with such an analysis. On the second account, processes of perceiving and reasoning about psychological beings are intimately connected: They are guided by the same system of knowledge.

In human infancy, we suggest, perception and reasoning are guided by a single knowledge system in at least three domains: physics, psychology, and number. We begin with the case of physics by reviewing the findings of studies of object perception and physical reasoning in infancy (see Spelke, 1990, or Spelke & Van de Walle, in press, for a more extensive review).

Perceiving and reasoning about physical objects

Research on object perception provides evidence that young infants can perceive the unity, boundaries, complete shapes, and persistence of objects under some conditions. Object perception appears to depend on amodal mechanisms that divide the surface layout into bodies in accordance with a small number of principles, each of which reflects constraints on object motion.

Consider first young infants' perception of the unity of a visible object. Experiments using preferential looking methods, which rely on infants' well-documented tendency to look longer at displays that they perceive to be novel, provide evidence that infants as young as 3 months of age perceive a three-dimensional object presented against a uniform background as a connected body that will maintain its connectedness as it moves. For example, infants who were familiarized with a cohesive object subsequently looked longer at the outcome of an event in which the object broke in two than at the outcome of an event in which the object moved as a whole (Spelke, Breinlinger, & Jacobson, 1992). Infants' preference for the former outcome reliably exceeded that of infants in a baseline condition who viewed the same outcome displays with no preceding events. The experiment provides evidence that infants perceived the original object as a connected body that should maintain its connectedness over motion.

Further experiments focusing on infants' preferential looking or object-directed reaching provide evidence that young infants perceive the distinctness of adjacent objects if the objects undergo different rigid motions (Hofsten & Spelke, 1985; Spelke, Hofsten, & Kestenbaum, 1989). Infants also perceive the distinctness of stationary objects if the objects are spatially separated: Spatially separated objects are perceived as distinct units even if they are separated only in depth such that the gap between them is not directly visible (Hofsten & Spelke, 1985; Kestenbaum, Termine, & Spelke, 1987; Spelke, Hofsten, & Kestenbaum, 1989).

The above findings suggest that infants perceive objects in accord with two constraints on object motion. First, objects are connected bodies that maintain their connectedness as they move: Two spatially separated objects, or two adjacent objects that slide with respect to one another, are therefore perceived as distinct. Second, objects are not connected to other objects and retain their separateness as they move: Two stationary and adjacent objects, lacking any spatially or spatiotemporally specified boundary, are therefore perceived as one connected body. These two constraints can be captured by a single *principle of cohesion*: Surfaces in the layout lie on a single object if and only if they are connected.

Now consider infants' perception of the unity of an object whose ends are visible or tangible but whose center is hidden. Four-month-old infants have been familiarized with such an object and then presented with a fully visible complete object or with two objects separated by a gap where the original object had been hidden. If infants perceived the original object as a connected body, then they should look longer at the two-object test display, relative to infants in a baseline condition who viewed the same test displays with no previous familiarization.

Such experiments provide evidence that 4-month-old infants perceive a visible, center-occluded object as a connected body if the ends of the object undergo a common rigid motion (Kellman & Spelke, 1983; Slater, Morison, Somers, Mattock, Brown, & Taylor, 1990; Craton & Baillargeon, personal communication, 1991). Rigid motion in any direction, including motion in depth, specifies the connectedness of the object (Kellman, Spelke, & Short, 1986); a pattern of common retinal displacement in the absence of true motion does not (Kellman, Gleitman, & Spelke, 1987). Studies in the haptic mode provide evidence that infants perceive the unity of objects whose ends are tangible under the same conditions as they perceive the unity of objects whose ends are visible (Streri & Spelke, 1988; 1989; Streri, Spelke, & Rameix 1992). Infants aged 4½ months held the two ends of a haptic assembly in their two hands, without visual or haptic access to the full assembly. They perceived the assembly as one connected body when the ends moved together and as two spatially separated bodies when the ends moved independently.

The findings of these studies suggest that infants perceive objects in accordance with two further constraints on object motion. First, surfaces move together only if they are in contact: The two rigidly moving ends of a center-occluded visible object or of a haptic assembly are therefore connected. Second, surfaces move independently only if they are spatially separated: Two independently movable seen or felt objects are therefore separated by a gap. These two constraints can be encompassed by a single *principle of contact*: Surfaces move together if and only if they are in contact.

Finally, consider infants' perception of objects that move fully out of view. Experiments using visual preference methods provide evidence that young infants perceive the persisting identity or distinctness of objects over successive encounters in accordance with the principle of contact (discussed earlier) and the principle of continuity: An object moves on exactly one connected path over space and time. First, Van de Walle and Spelke (1993) presented infants with an object that moved back and forth behind an occluder such that its two ends were visible in immediate succession but never simultaneously: The left side of the object moved behind the occluder until the object was fully hidden, and then the right side of the object began to appear from behind the opposite side, moving at the same speed and on the same path. Subsequent looking preferences between nonoccluded complete and broken displays provided evidence that the infants perceived the object as a connected body, in accordance with the contact principle. Second, Spelke and Kestenbaum (1986) and Xu and Carey (1992) presented infants with events in which an object moved out of view behind the first of two spatially separated occluders, and after a pause an object moved into view from behind the second occluder. Subsequent visual preferences between fully visible one- and two-object displays provided evidence that infants perceived two objects in this event in accordance with the continuity principle: Because no object appeared between the two screens, the object moving on the left must have been distinct from that on the right.

In summary, young infants appear to perceive objects in accordance with the principles of cohesion, contact, and continuity. We now consider whether infants respect these principles when they reason about objects that move from view.

A variety of experiments provide evidence that young infants represent the existence of an object that moves from view and make certain inferences about the object's continued motion (e.g., Baillargeon, 1986; Leslie, 1991; Spelke, Breinlinger, Macomber, & Jacobson, 1992). These experiments have used preferential looking methods to assess infants' reactions to an "invisible displacement task" (Piaget, 1954), in which an object moves from view and infants must infer its further motion. The experiments provide evidence that infants make some, but not all, of the inferences about object motion made by older children and adults. A consideration of infants' successes and failures may thus shed light on the principles guiding infants' inferences.

Experiments from three laboratories offer evidence that infants' inferences accord with two constraints on object motion: continuity (objects move only on connected paths), and solidity (objects move only on unobstructed paths, such that two objects never occupy the same place at the same time) (Baillargeon, 1986; Leslie, 1991; Spelke et al., 1992). In one experiment (Spelke et al., 1992, Exp. 1), 4-month-old infants first were familiarized with an event in which a ball fell behind a screen on an open stage and was revealed on the stage floor. Then a second surface was placed above the stage floor and a test sequence was presented in which the ball fell behind the screen, and the screen was raised to reveal the ball at rest either on the upper surface or on the lower surface. The latter position was inconsistent with the continuity and solidity constraints, because the ball could reach the lower surface only by jumping discontinuously over or by passing through the upper surface. Infants looked longer at the inconsistent than at the consistent test outcome. Their preference for the inconsistent outcome reliably exceeded the preferences of infants in a separate control condition, who viewed the same outcome displays preceded by consistent events. The experiment therefore provides evidence that 4-month-old infants infer that a hidden object will move on a connected and unobstructed path, in accordance with the continuity and solidity constraints. Further experiments provide evidence for the same ability at ages ranging from $2^1/_2$ months to 10 months, with a variety of displays and events (e.g., Baillargeon, 1986; Baillargeon, Graber, DeVos, & Black, 1990; Leslie, 1991; Spelke et al., 1992).

The continuity and solidity constraints are closely related: Whereas the continuity constraint dictates that an object must move on at least one connected path (i.e., the path of an object can contain no gaps), the solidity constraint dictates that an object must move on at most one connected path (i.e., the paths of two objects cannot intersect in space and time). Both constraints therefore can be captured by the principle of continuity: An object traces exactly one connected path.

Additional experiments provide evidence that infants infer that a hidden object will move in accordance with the principles of cohesion and contact. Carey, Klatt, and Schlaffer (1992) tested 8-month-old infants with events in which one object was lowered, raised, and lowered again behind a screen, and then the screen was raised to reveal one or two objects on the display floor. Infants looked longer at the two-object event, relative to the length of infants' looks in a baseline control experiment. The experiment provided evidence that infants inferred that the object would move in accordance with the cohesion principle: Unlike nonsolid substances (which were tested in other experiments), moving objects do not leave parts of themselves behind. Ball (1973) familiarized infants with an event in which one object moved out of view behind a screen and then a second object, which was initially half visible and stationary, moved fully into view. Then infants were tested with nonoccluded displays in which the first object either came into contact with the second object or stopped short of the second object. Infants looked longer at the no-contact event, relative to baseline controls. The experiment provides evidence that the infants inferred that the first object contacted the second object, in accordance with the contact principle (for further evidence, see Leslie, 1988).

In summary, infants appear to infer that hidden objects will move in accordance with the principles of cohesion, contact, and continuity. These are the same principles that guide infants' perception of the unity, boundaries, and persistence of the objects they see and feel. A single system of knowledge therefore appears to underlie object perception and physical reasoning in infancy. We now ask briefly whether a single system of knowledge also guides infants' perception and reasoning in the domains of psychology and number.

Perceiving and reasoning about persons

The system of knowledge guiding reasoning about human action and mental life is currently a subject of much study and some debate (see Astington, Harris, & Olson, 1988; Leslie, 1987; Perner, 1991; Wellman, 1990). Central to our understanding of other human beings, however, appears to be the notion that people are sentient beings who choose their actions (see Wellman, 1990, for a discussion). If this notion is central to reasoning about human action, then the system of knowledge of psychology is distinct from that of physics. We must ask, therefore, how reasoners single out a person as an entity in the domain of their psychological reasoning.

Babies appear to have an innate representation of the structure of the human face; this representation allows neonates to direct attention to faces that move across the field of view (see Johnson & Morton, 1991, for a review). Perhaps babies use that representation to identify people as entities expected to be capable of perceptions and purposive action. Evidence from a number of sources suggests this is not the case: Infants, children, and adults identify animate, sentient beings by taking account of their actions, not by analyzing their surface appearance.

Consider first young children's reactions to dolls. Many young children are delighted by dolls, with whom they engage in rich pretend interactions. At no age, however, do children appear to be led by dolls' human features to treat dolls as animate, sentient beings (R. Gelman, 1990; R. Gelman, Spelke, & Meck, 1983). Even infants respond differently to dolls and to living faces: A stationary doll's face is an object of interest or delight, whereas a stationary human face, seen under similar circumstances, can evoke fear or aversion (Tronick, 1982). In addition, young infants appear to respond to objects that lack any clearly animate features (e.g., mobiles) as animate and social beings, if the behavior of those objects approximates the behavior of a responsive social agent. These findings, and other findings with adults (Heider & Simmel, 1944), suggest that children and adults use some principles of their intuitive psychology not only to reason about persons but also to perceive persons as persons (for more detailed expositions of this view, see R. Gelman, 1990; and Premack, 1990).[1]

Perceiving and reasoning about number

The origin and the nature of knowledge of number has been a topic of philosophical debate at least since Hume (e.g., Kitcher, 1983). Psychological research on infants (e.g., Wynn, 1992) and animals (see Gallistel, 1990, for a review) strongly supports the existence of innate knowledge of number that includes core principles of one-to-one correspondence and succession (every number has a unique successor, Gallistel & R. Gelman, 1992). If this view is correct, then number would appear to be a domain of knowledge distinct from physics or psychology. How do reasoners single out the entities in this domain, apprehending sets and their numerosity?

A controversy exists concerning the relations between perceiving and reasoning about small sets. On one view, perception of small sets depends on a special pattern-recognition process, "subitizing," whereas perception of large sets depends on a counting process (Klahr & Wallace, 1973; Davis & Pérusse, 1988). The principles of operation of the subitizing process are unknown, but they are believed to be distinct from the principles governing numerical reasoning. On a different view (Gallistel, 1990; Gallistel & R. Gelman, 1992), sets of all sizes are enumerated by a counting process. Proponents of both views agree that the principles at the core of the counting process include one-to-one correspondence and succession, and that these principles underlie not only counting but also the operations of spontaneous arithmetic.

In our terms, the difference between these two views of the process of enumerating small sets is exactly the difference between the thesis that a single system of knowledge underlies number perception and numerical

reasoning, and the thesis that distinct systems underlie these abilities. Note that on both views, a single set of principles is thought to enable humans to perceive and reason about large sets.

In summary, domain-specific reasoning and domain-specific perception appear to depend on a single system of knowledge in the domains of physics, psychology, and number (at least for large sets). We now ask how knowledge grows and changes in these domains.

Cognitive development

It is natural to suppose that humans learn about the world by observing it. We learn that bodies fall by watching them fall; we learn that insults make people angry by watching people react to insults; we learn that $2 + 2 = 4$ by observing two sets of two things combine into one set of four things. Variants of this thesis may be offered. Children may learn through active manipulation (releasing or throwing objects, hitting people, combining sets), or by social interaction (tossing balls around, participating in social exchanges, playing number games).

If any of these proposals is correct, then children and adults will learn only about the things they perceive. A child who cannot perceive any object that falls, any person who is moved to anger, or any sets of two things that combine into a set of four things, will never learn about these entities, however much he or she observes, manipulates, or communicates about the surrounding layout. Perception limits the development of knowledge.

The consequences of this limit depend on the relation between the principles governing perception and those governing reasoning. If perception and reasoning are guided by distinct principles, experience may overturn the original principles governing reasoning. For example, suppose that perception of persons depends on a face-recognizer, whereas initial reasoning about persons depends on notions that action is internally generated in accordance with perceptions and feelings. Encountering a doll, the child would perceive a person. The behavior of this person, however, would not appear to result from choices but from the blind operation of the laws of mechanics. Because the doll must be admitted to the class of persons (we are assuming that the face-recognizer, not the psychological reasoner, makes this decision), the child is now in a position to learn that his or her initial psychology is false: Not all persons are purposive, sentient beings. With increased exposure to dolls, stuffed animals, portraits, and the like, this learning will grow and be extended. Learning will therefore bring changes to the child's initial system of knowledge.

If the same system of knowledge guides perception and reasoning, in contrast, it would seem that children *cannot* learn, by observing the world, that their initial system of knowledge is false. For example, suppose that both perception and reasoning about persons are guided by the notion that people are sentient and purposive. When children encounter an entity that looks like a human being but does not engage in self-generated action, they will not conclude that their notion of person is false but rather that this entity does not fall within the domain of their psychology: It is not a person.

In any domain in which perception and reasoning depend on the same system of knowledge, learning from observation, from action, or from social interchange will tend to preserve the initial system of knowledge. Knowledge will grow by a process of enrichment, whereby core principles become further entrenched. The initial system of knowledge will not be overthrown by any process of induction from experience, because only objects that conform to that system are available to be experienced. Cognitive development will result in the enrichment of knowledge around unchanging core principles.

Some aspects of mature, commonsense reasoning appear to support the view that knowledge of physical objects, persons, and number develops by enrichment. In the domain of physics, principles such as cohesion, contact, and continuity appear to be central to mature intuitions about object persistence (see Hirsch, 1982) and object motion (see Spelke, 1991, for discussion). In the domain of psychology, the notion that people choose their actions appears to be deeply ingrained in mature commonsense reasoning (Wellman, 1990). Finally, in the domain of number, Gallistel and R. Gelman (1992) argue that the most intuitive mature conceptions of number are those that derive from the principles of one-to-one correspondence and succession.

Nevertheless, this reasoning leads to a contradiction. Conceptual change in the domains of physics, psychology, and number is not only possible but actual. In the history of science and mathematics, it has occurred with the development of Newtonian and quantum mechanics, with the attempt to construct a purely behavioristic or mechanistic psychology, and with the discovery of rational, real, and complex numbers. In each of these cases, the development of science has led to the construction of new principles and to the abandonment of principles that formerly were central to knowledge in the domain. In each of these cases, new types of entities were discovered or posited. The existence of conceptual change in science challenges the view that knowledge develops by enrichment around a constant core, and it raises the possibility that there are no cognitive universals: no core principles of reasoning that are immune to cultural variation.

Conceptual change

The nature and existence of conceptual change has been extensively analyzed and debated since Feyerabend (1962) and Kuhn (1962) independently adopted the mathematical term "incommensurability" (no common measure) to refer to mutually untranslatable theoretical languages (see Suppe, 1977, for a comprehensive critique of the early Kuhn/Feyerabend positions). These debates have led to a softening of Kuhn's and Feyerabend's early claims. In

particular, current analyses of conceptual change in science deny that the meanings of all terms in a theory change when some do, that theories completely determine evidence and therefore are unfalsifiable, or that theory change is akin to religious conversion. These analyses nevertheless hold that the core insight of the Kuhn/Feyerabend early work stands: The history of science is marked by transitions across which students of the same phenomena speak incommensurable languages.

Carey (1991) summarizes the recent analyses of conceptual change that have been offered by philosophers of science (Kitcher, 1988; Kuhn, 1982; see also Hacking, 1993; Nersessian, 1992) and by cognitive scientists (Thagard, 1988; see also Chi, 1992; Vosniadou & Brewer, 1992). Conceptual change consists of conceptual differentiations, such that the undifferentiated parent concept plays no role in subsequent theories (Carey, 1991; Kuhn, 1977), and of the creation of new ontological categories (Thagard, 1988; Chi, 1992). Conceptual change involves change in the core principles that define the entities in a domain and govern reasoning about those entities. It brings the emergence of new principles, incommensurable with the old, which carve the world at different joints.

Cognitive science and the history of science

Some doubt the relevance of historical analyses of conceptual change to cognitive science and especially to cognitive development. Scientific reasoning and concepts, one might argue, are different from ordinary reasoning and concepts. Only the former undergo changes in core principles.

We consider it a serious empirical question as to whether the core concepts of commonsense reasoning are subject to change. Whatever answer one gives to this question, however, the existence of conceptual change in science challenges the argument for enrichment given above. If the development of domain-specific reasoning is constrained by domain-specific perception, and if the same system of knowledge underlies both reasoning and perception, then no person at any level of expertise is in a position to learn that his or her initial system of knowledge is false. This argument applies to any perceiver and reasoner, whether human or animal, layperson or scientist. The existence of conceptual change in domain-specific core knowledge presents a serious counterexample to the argument for enrichment and needs to be explained (Carey, 1991).

Those who emphasize the differences between intuitive theories and explicit scientific theories often imply that those differences in themselves *explain* conceptual change. In particular, the community of scientists, the self-reflective nature of explicit theory construction, and the instructional institutions that create scientists may be engines of conceptual change (e.g., Spelke, 1991). We grant that developed science differs from intuitive knowledge in these three ways. Nonetheless, communication among scientists, reflection, and instruction do not in themselves provide a mechanism for conceptual change.

First, processes that occur within an interactive community of scientists cannot, in themselves, bring about conceptual change, because the interactions within a scientific community can only be as effective as the conceptions of its individual members permit. Communication between scientists succeeds only insofar as two scientists can single out the same things to talk about (see Kuhn, 1962). The arguments against the possibility of conceptual change therefore apply to the community of scientists as well as to the individual scientist.

Next, consider the possibility that reasoners use "disciplined reflection" to revise conceptions within a domain. Many have argued that metacognitive abilities enable human intelligence to extend itself beyond its initial limits (e.g., Rozin, 1976; Sperber, this volume). By itself, however, reflection can do nothing to extricate developing conceptions from the self-perpetuating cycle described above. We as humans can only reflect on the entities we perceive. If our initial conceptions determine those entities, then we will be able to reflect only on entities whose behavior accords with our initial conceptions. Reflection by itself will not produce conceptual change.

Finally, instructional institutions that create scientists cannot in themselves account for conceptual change, for two reasons. First, instruction cannot account for individual discovery or invention. Second, instruction, like all communication, is limited by the student's ability to apprehend the objects to which it applies. If a student is not able to apprehend the entities in a to-be-learned theory, he or she may mouth the correct words but will assign to them meanings licensed by his or her own concepts (see the science misconceptions literature reviewed in Carey, 1986, and the chapter by Vosniadou, this volume).

In sum, we do not dispute that Western science is a social process, the product of self-reflective, metaconceptually sophisticated adults, and that systematic instruction is required to form these adults. These facts, however, do not provide an account of conceptual change. We require such an account: an explanation of how a reasoner can move beyond the core principles in a system of knowledge. Once such an account is provided, we may ask how it tempers the generalization that knowledge develops by enrichment around a constant core.

Mechanisms of conceptual change

Mappings across domains

The formal reflections of scientists provide one source of evidence concerning the processes of conceptual change. We begin with the reflections of the physicist, historian, and philosopher of science, Pierre Duhem. Duhem (1949) suggested that scientific physics is not built directly upon commonsense understanding of physical phenomena but depends instead on translations

between the language of ordinary experience and the language of mathematics. According to Duhem, the objects of science are not concrete material bodies but numbers. To provide explanations for physical phenomena, physicists first translate from a physical to a mathematical description of the world, and then they look for generalizations and regularities in the mathematical description. These generalizations, when translated back into the language of everyday objects, are the physicist's laws.

In our terms, scientists who effect a translation from physics to mathematics are using their innately given system of knowledge of number to shed light on phenomena in the domain of their innately given system of knowledge of physics. Scientists do this by devising and using systems of measurement to create *mappings* between the objects in the first system (numbers) and those in the second (bodies).[2] Once a mapping is created, the scientists can use conceptions of number to reason about physical objects. They therefore may escape the constraints imposed by the core principles of physical reasoning. In effect, the mapping from physics to number creates a new perceptual system for the domain of physics, centering not on the principles of cohesion, contact, and continuity but on the principles of one-to-one correspondence, succession, and the like. The entities picked out by this new perceptual system need not be commensurable with those picked out by the old.

Duhem focuses exclusively on the construction of a translation, or mapping, from physics to mathematics. Conceptual change may occur as well through mappings across other domains. In particular, conceptual changes in science appear to have resulted from the construction and use of mappings from psychology to physics. By viewing animals and people as complex machines, mechanistic biology and mechanistic psychology aim to explain animal and human action in terms of physical principles. We return to these conceptual changes below.

How do scientists construct mappings across domains? Science's informal documents (lab notebooks, journals) provide an excellent source of data concerning this process. Recently, cognitive scientists as well as historians and philosophers of science have begun to mine this source (e.g., Gruber, 1974, on Darwin; Nersessian, 1992, on Maxwell; Tweney, 1991, on Faraday). Nersessian (1992) concentrates on two interconnected pairs of processes that recur in historical cases of conceptual change: (1) the use of physical analogy, and (2) the construction of thought experiments and limiting case analyses. These processes serve both to reveal tensions and inadequacies within a system of knowledge and to restructure that system through the construction of mappings across knowledge domains.

Physical analogies

Nersessian's analysis of Maxwell's use of physical analogies provides a worked example of the productive use of such mappings in the process of conceptual change. According to Nersessian, Maxwell himself used the term "physical analogy" in explaining his method. A physical analogy exploits a set of mathematical relationships as they are embodied in a source domain, so as to analyze a target domain about which there is only partial knowledge. In Maxwell's case, the source domain was fluid mechanics as an embodiment of the mathematics of continuum mechanics, and the target domain was electromagnetism. By constructing the analogy between these two areas of physics, Maxwell was able ultimately to construct an effective mathematical theory of electromagnetism.

Nersessian notes several important lessons from this case study. First, the analogy from fluid mechanics to electromagnetism did real inferential work: Important mistakes in Maxwell's first characterization of the electromagnetic field are traceable to points at which this analogy breaks down. Second, the process of constructing mappings across domains is difficult: Each mapping must be explored and tested in depth to determine its usefulness. Third, "imagistic representations" play an important part in constructing the mapping from physics to number: They express mathematical relationships in a directly comprehensible way and thus serve as a good bridge between domains. Fourth, the process of constructing a mapping across domains is not one of transferring the relations from source domain to target in one fell swoop by plugging in and testing values. Rather, a scientist explores different possible mappings from the source domain onto the target domain, imposing different conceptualizations of the target domain in so doing. Finally, the mapping thus created can produce conceptual change in both domains. By using the Newtonian mathematics of continuum mechanics to understand electromagnetic fields, Maxwell constructed a mathematics of greater generality than that of his source domain (Nersessian, 1992).

Thought experiments and limiting case analyses

Another modeling activity is the construction of thought experiments, including limiting case analyses. Philosophers of science have often discussed how (or whether) thought experiments can be *experimental*: Can they have empirical content even though they involve no data? Kuhn (1977), analyzing a thought experiment that figured in the process by which Galileo differentiated instantaneous velocity from average velocity, argued that one function of thought experiments is to show that current concepts cannot apply to the world without contradiction. Nersessian (1992) extended Kuhn's analysis by arguing that thought experiments involve mental model simulations, which are part of the source of their empirical content.

Nersessian's example is Galileo's famous thought experiment showing that heavier objects do not fall faster than lighter ones. Galileo imagined two objects, a large heavy one and a small light one, in free fall. According to Aristotelian and scholastic physics, the heavier object should fall faster. He

then imagined joining the two objects with an extremely thin rod, creating a composite object. This thought experiment suggests two contradictory outcomes: (1) The composite object is heavier still and therefore should fall even faster, and (2) the slower speed of the smaller object should impede the speed of the larger object, so the composite object should fall more slowly! Galileo went on to construct a limiting case analysis concerning the medium in which objects fall to resolve the contradiction. He concluded that in a vacuum, objects of any weight will fall at the same speed. This thought experiment and limiting case analysis played a role in constructing a differentiated, extensive conception of weight. That conception, in turn, depends on the mathematical distinction between a sum and an average.[3]

Conceptual change and cognitive universals

If processes such as those discussed by Nersessian are necessary components of the engine for conceptual change, we can account for the plausibility of the intuition that conceptual change results from the cooperative activity of a scientific community, from reflection, and from instruction. Galileo, Maxwell, Faraday, Einstein, and Darwin left writings, diaries, and notebooks showing that they used the heuristic processes Nersessian describes, and that they were fully conscious of doing so. They used these processes in the context of a self-reflective understanding of the goal of constructing new scientific theories. When one constructs a mapping across domains for the first time, one never knows how useful or deceptive it will prove to be. Thought experiments, physical analogies, and limiting case analyses serve as devices to communicate new conceptualizations to the scientific community, but these new conceptualizations will be adopted only insofar as they provide resolutions to standing puzzles and promote a productive research program. The jury is the social institutions of science.

But do heuristic processes of the kind Nersessian describes, and the mappings that result from them, also occur outside of developed science? Do they bring conceptual change to lay adults and children, creating cultural differences in core knowledge systems? The evidence considered thus far is consistent with three different hypotheses concerning conceptual change outside of science, each with different consequences for the existence of cross-cultural cognitive universals.

According to the *strong universality hypothesis*, only metaconceptually sophisticated scientists can overturn the core principles that innately determine ontology and reasoning. If this hypothesis is true, then the intuitive theories of people in all cultures will be enriched versions of those innate principles. The core principles of commonsense reasoning will be universal.

According to the *weak universality hypothesis*, children and lay adults can overturn innate, core principles of reasoning, but only through experience in a culture with a developed science. The source of conceptual change is the assimilation by children of the conceptions of the adults around them as those conceptions are expressed in adult language, in the measurement devices and technology of the culture, and in systematic instruction in school. And the source of the lay adult's conceptions, in turn, is the cultural assimilation of conceptual changes *originally* made by metaconceptually sophisticated scientists. If the weak universality hypothesis is true, then the intuitive knowledge systems of all cultures will share a common innate core, except in the case of cultures with a developed science.

According to the *no universality hypothesis*, the processes of conceptual change observed in scientists also occur spontaneously in children and lay adults. Although infants the world over share a set of initial systems of knowledge, those systems are spontaneously overturned over the course of development and learning, as children and adults construct, explore, and adopt mappings across knowledge systems. Because of the diversity of the potential mappings across domains, it is unlikely that the knowledge systems of members of different cultures will share a common core.

In the rest of this chapter, we turn to evidence bearing on these hypotheses. Rather than rely on cross-cultural data, we will examine a population that stands outside the cultural institutions of science and that lacks metaconceptual awareness of theory construction and choice: American children. Even though children do not engage in the social process of explicit theory construction and are not self-reflective theorizers, there is ample empirical evidence for conceptual change in childhood. Conceptual change occurs both spontaneously, as the child masters the language and the intuitive knowledge systems of the adult culture, and also as the result of systematic instruction in school. The existence of conceptual change in childhood militates against the strong universality hypothesis.

Conceptual change in childhood

Number

The preschool child's concept of number is the *positive integer* (see R. Gelman, 1991), as defined by the core principles of one-to-one correspondence and succession. This core notion changes early in the child's school years as the child constructs the concept of *0* (Wellman & Miller, 1986), the concept of *infinity* (in the form of a realization that there is no highest number; R. Gelman & Evans, 1981), and the concept of *rational number* (R. Gelman, 1991), and as the child becomes explicitly aware of the core principles defining number and thereby becomes able to reason about conservation of number (see R. Gelman & Gallistel, 1978, for a review).

It could be argued that the construction of *0* and *no highest number* involve change in the concept of number, as both changes begin to separate number from counting. Moreover, the construction of the concept of *rational number*

brings an even deeper conceptual change. Coming to see .5 or $^1/_3$ as numbers requires abandoning the identification of number with counting, abandoning the successor principle, and constructing a new understanding of division (as a different operation from repeated subtraction). The new principles that jointly determine what constitutes a number and that govern reasoning with numbers include closure under division, construed in this new way.

R. Gelman (1991) suggested that changing conceptions of number depend in part on the construction of mappings between number and physical objects (as the child learns measurement) and on the construction of mappings between number and geometry (via devices such as the number line). Children's ability to benefit from these mappings suggests that the strong universality thesis is false for the domain of number. It is not clear, however, whether children or adults would spontaneously devise measurement devices or construct number lines in the absence of a developed science and mathematics. The weak universality hypothesis and the no universality hypothesis are both consistent with the above studies.

Biology and psychology

The principles determining the entities of the earliest psychology – capacity for self-generated motion and attention and contingent reaction to surrounding events – actually determine the ontological kind *animal*, not just *person*. For this reason, Carey (1985) speculated that young children's intuitive biology is not differentiated from their intuitive psychology. Her claim that 4-year-olds do not have an autonomous domain of intuitive biology has come under much scrutiny (e.g., Inagaki & Hatano, 1988; Springer & Keil, 1989; Wellman & S. Gelman, 1992). Regardless of whether preschool children should be granted an autonomous biology, however, it is clear that their understanding of biological phenomena differs radically from that of older children. In Hatano and Inagaki's (1987) terms, children progress from a vitalistic biology to a mechanistic biology.

Much of the evidence for this conceptual change was reviewed in Carey (1985, 1988): Evidence for the differentiation of the concepts *dead* and *inanimate*, for a change in the status of *person* as *animal*, and for the coalescence of the concepts *animal* and *plant* into a new concept, *living thing*. To that evidence, Keil and his colleagues have added many new phenomena suggesting conceptual change over these years (Keil, 1989; Springer & Keil, 1989). Keil's data serve two important purposes: They provide information concerning the precise characterization of the preschool child's initial biological concepts, and they provide evidence for conceptual change in the concept of *animal* and perhaps the concept of *person*.

Take Keil's transformation studies. Preschool children believe that a skunk can be turned into a raccoon through surgery; by age 9 (and earlier in some studies), children believe that the animal resulting from such a transformation is still a skunk that just looks like a raccoon (Keil, 1989). Preschool children do not think, however, that anything that looks like a raccoon is a raccoon: A skunk wearing a raccoon costume and pictured to look identical to a raccoon is judged to be a skunk (Keil, 1989). Similarly, a dog with all its insides removed (the blood and bones and stuff like that) is judged not to be a dog any more (S. Gelman & Wellman, 1991). These data suggest that to preschool children, the core of the notion of *animal kind* includes bodily structure: It is not enough to look just like an animal (e.g., a stuffed dog) or a particular kind of animal (e.g., a raccoon-costumed skunk), in order for an entity to be an animal or a particular kind of animal. Rather, the body of the entity must have the right structure, including internal structure. But these data also show that 9-year-olds have constructed a deeper notion of how that bodily structure must come to be: For 4- to 6-year-olds, surgery will do it; for 9-year-olds, bodily structure must result from a natural growth process. We take this developmental difference to reflect changes in the principles that define the entities in the domain of biology: By age 9, aspects of the life cycle have become part of the core principles. Changes of this sort are typical of historical cases of conceptual change (Kitcher, 1988).[4]

That this change actually reflects conceptual change rather than enrichment is further shown by changes in children's understanding of why children resemble their parents. Both Springer and Keil (1989) and S. Gelman and Wellman (1991) claim that preschool children understand that babies (including animal babies) inherit an innate potential from their parents to develop certain traits rather than others. However, their data do not establish that the preschool child has an understanding of the *biological* inheritance of properties.

We take an understanding of inheritance of properties to include, at a minimum, two essential components. First, children resemble their parents: Black parents tend to have black children, blue-eyed parents are more likely to have blue-eyed children than are brown-eyed parents, dogs have baby dogs rather than baby cats, and so on. Second, the *mechanism* underlying this resemblance crucially involves birth. There are many ways children may come to resemble their parents: Curly-haired parents may have curly-haired children because they give them permanents; prejudiced parents may have prejudiced children because they taught them to be so. Such mechanisms are not part of a biological process of inheritance of properties. To be credited with a biological concept of inheritance, children need not understand anything like a genetic mechanism, but they must distinguish the process underlying family resemblance from mechanical or psychological processes. At a minimum, children should realize that the process through which an animal originates – birth – is crucially involved in the process through which animals come to have their specific characteristics.

Without doubt, preschool children understand that offspring resemble their parents. Springer (1992) told 4- to 8-year-olds that a pictured animal had an

unusual property (e.g., this horse has hair inside its ears) and then probed for projection of the property to a physically similar horse, described as a friend who is unrelated to the target, and to a physically dissimilar horse, described as the target's baby. At all ages, the property was projected more to the baby than to the friend. This important result confirms the mounting evidence that preschool children are not appearance-bound (S. Gelman, Coley, & Gottfried, this volume) and establishes the family resemblance component of a belief in inheritance of properties. However, because Springer did not probe the mechanism responsible for inheritance, his study does not bear on the second component. Springer distinguished what he considers a biological relationship (parentage) from a social relationship (friendship), but, as Carey (1985, 1988) points out, parentage is also a social relationship. At a minimum, one would like to see biological parentage distinguished from adoptive parentage.

The same issue arises with respect to the data of Springer and Keil (1989). Four- to seven-year-old children, plus adults, were told that both parents have a particular atypical property (e.g., pink rather than the usual red hearts) and were asked whether an offspring would have that property. They manipulated further information about the unusual property (whether the parents were born with the property or acquired it in an accident, whether the property was internal or external to the body, and whether the property had "biological" functional consequences).[5] Two important results emerged. First, only adults based their judgments solely on information about how the parents acquired the property: That is, only adults related birth to inheritance. In one study, 7-year-olds were beginning to take this variable into account. Second, even preschool children made systematic judgments, influenced by whether or not the property was described as having biological consequences. From this result, Springer and Keil concluded that preschoolers have a biological concept of inheritance, but that it is different from the adult's concept. Again, a comparison between natural parentage and adoptive parentage is necessary to determine whether preschoolers' concept of inheritance goes beyond an understanding of family resemblance.

S. Gelman and Wellman (1991) specifically contrasted nature versus nurture. For example, they asked whether a cow, Edith, who had been separated from other cows at birth and raised with pigs, would (1) moo or oink and (2) have a straight or curly tail. Even 4-year-olds judged that Edith would moo and have a straight tail. But the story asserts that Edith is a cow, in spite of having been raised in the company of pigs. There is a wealth of evidence, much of it from Gelman herself (S. Gelman, Coley, & Gottfried, this volume), that preschoolers take category membership as predictive of category-relevant properties, even in the face of conflicting information. Furthermore, the task does not stress that the baby cow is raised in a pig family, a child among other children who are pigs. S. Gelman and Wellman also posed a story about a seed from an apple, planted in a flower pot, and found that by age 5, children judged it would come up an apple rather than a flower. This scenario contrasts environment (in the company of flowers) with parentage (seed from an apple) and confirms Springer's (1992) finding that *family* resemblance is crucial. The experiment does not provide evidence, however, for an understanding of biological inheritance and a differentiation between biological and adoptive parentage.

Solomon, Johnson, Zaitchik, and Carey (1993) have carried out several studies contrasting adoptive with biological parentage. For example, a story is told about a (tall) shepherd whose son is taken at birth to be adopted by a (short) king and raised as the prince. The child is then asked whether the boy, when he grows up, will be tall like the shepherd or short like the king. Adults project physical properties such as height on the basis of biological parentage. This pattern does not begin to emerge until age 7: the age at which Springer and Keil (1989) begin to see the effect of information as to whether the property of the parent was inborn or acquired. As of now, there is no evidence that preschoolers have a conception of biological inheritance that goes beyond expectations of resemblance between parents and their offspring.

These data are consistent with those reviewed in Carey (1985), indicating changes in children's understanding of reproduction during the early school years. Preschool children do not take reproduction as one of the core principles defining animals and governing inferences about them. By age 10, in contrast, knowledge of reproduction begins to organize children's understanding of animals, as reflected both in the beginning understanding of inheritance and as reflected in judgments of what makes a skunk a skunk (Keil, 1989). This change is part of the construction of the new ontological category, *living thing*, which includes plants as well as animals (Carey, 1985). New core principles and new entities in the domain are hallmarks of conceptual change.

How do these fundamental changes in children's concept of *animal* bear on children's innate concept of *person*? Does the notion of a person as a sentient, freely acting being change once children begin to construct a mechanistic biology? If so, how does this change come about, if the principles at the center of the initial concept of person underlie not only psychological reasoning but also perception of persons?

Although answers to these questions are far from clear, we offer the following observations. First, biological concepts appear to exert some influence on mature, commonsense psychology. For example, Western adults are inclined to consider the living descendant of two persons as a person, even if that person lacks all capacity to act (e.g., while sleeping or in a coma). Adults also are inclined to deny personhood to apes, dolphins, and parrots, however impressive their behavioral accomplishments. *Person* is, at least in part, a species concept (see, e.g., Wiggins, 1980). Second, the initial conception of a person as a freely acting, sentient being remains a powerful part of Western adults' commonsense understanding of human action, surviving in uneasy coexistence with the later-developing biological conception. Tensions between

these conceptions can be found not only in scientific psychology and philosophy of mind but also in everyday life, as current debates over abortion, criminal responsibility, and other topics demonstrate.

Finally, note that the development of mechanistic biology and mechanistic psychology depend in part on the construction of mappings across the domains of psychology and physics. The research reviewed above provides evidence that the construction of these mappings is a difficult and extended process. Insofar as it succeeds, however, there arises the possibility for conceptual change. A person may be viewed not only as a free agent but also as a complex machine and a member of a living kind (see Gentner & Grudin, 1985, for a historical analysis of changes in metaphors for the mind over 90 years of scientific psychology).

Studies of American children's changing biological and psychological conceptions cast doubt on the strong universality hypothesis, but they do not distinguish between the weak and the no universality hypotheses. To explore the conjecture that conceptual change in biology and psychology requires a developed scientific tradition, we need empirical studies of the intuitive biological and psychological theories held by children and adults in a wide range of cultures. Atran (1990) finds evidence for cross-cultural universality of folk taxonomies in biology but does not review research on folk explanations of biological phenomena: disease, reproduction, inheritance, and the functions of body parts. To our knowledge, the only work exploiting recent methodologies to diagnose intuitive biological conceptions is that of Jeyifous (1986), building on the work of Keil (1989). Jeyifous's results suggest that the developing conceptions of biology sketched in this section occur in cultures isolated from Western biological thought. For example, unschooled rural Yoruba children shift from the judgment that an operated-upon raccoon has become a skunk to the judgment that it is still a raccoon at about the same age as their American counterparts. If this shift reflects conceptual change, then Jeyifous's finding suggests two conclusions. First, conceptual change does not require developed scientific institutions. Even though Yoruba biology differs greatly from intuitive American biology, both involve a notion of animal kind that is deeper than bodily structure, whereas the preschool child's biology (in both cultures) does not. Second, even though conceptual change is seen in both cultures, cross-cultural universality is still observed. Of course, whether intuitive Yoruba biology is commensurable with intuitive American biology is an open empirical question.

Matter and physical objects

We have suggested that objects, for babies, are defined by the principles of cohesion, continuity, and contact: Objects are coherent solids that maintain their boundaries as they move along spatiotemporally continuous paths, and that act upon each other only on contact. There are tensions in the baby's application of these principles, however, and these tensions may provide the seeds for future conceptual change. The principles do not apply equally well to persons (who commonly appear to violate the contact principle, while behaving in accord with the principles of cohesion and continuity). Similarly, nonsolid substances such as liquids, gels, and powders obey the principle of continuity (e.g., sand cannot pass through solid barriers) but not the principle of cohesion (e.g., sand can disperse and coalesce as it moves). Although innate principles determine an ontology for the child, they do not define entirely nonoverlapping sets of entities. How do children conceptualize the entities in the overlapping sections of their ontological universe, and how do their conceptions change with development and experience? We focus here on changing conceptions of nonsolid substances and on emerging conceptions of *matter*.

The distinction between objects and nonsolid substances is very salient to young children. Objects are typically quantified as individuals whereas nonsolid substances are typically not quantified as individuals. This quantificational distinction is marked as the count/mass distinction in the syntax of many of the world's languages, and it conditions 2-year-old children's hypotheses about word meaning (Soja, Carey, & Spelke, 1991). But do young children appreciate that both objects and nonsolid substances are material?

Four-year-old children treat both objects and nonsolid substances as subject to the continuity principle: They judge that it is impossible for water to fill a box if the box is already filled by a steel block of the same dimensions (Carey, 1991). Moreover, 3- and 4-year-olds distinguish objects from ideas, dreams, and images on the basis of two properties that are relevant to the distinction between material and immaterial entities: objective perceptual access and causal interaction with other material entities (Estes, Wellman, & Woolley, 1989). Children's abilities to distinguish some material entities (i.e., objects) from some immaterial entities (i.e., ideas) on the basis of some properties that for adults are part of the core of the distinction between material and immaterial entities does not show, however, that children draw a material/immaterial distinction. Rather, children might draw a distinction between objects and mental entities, or between real and imaginary entities, on the basis of these properties. Two types of further information are required before we attribute a material/immaterial distinction to the child: We need to probe more widely the entities that fall under the distinction, and we need to analyze the explanatory work the distinction does for the child, in relation to the explanatory work that the material/immaterial distinction does for adults.

Carey (1991) presents such an investigation and concludes that preschool and early elementary-aged children *do* draw a material/immaterial distinction. The child's concept of matter, however, is incommensurable with that of the adult. Conceptual change in the years from 4 to 12 involves each of the interrelated concepts of *matter*, *kind of stuff*, *weight*, *density*, and *air*. The analysis includes two examples of initially undifferentiated concepts that are

incommensurable with adult concepts: *weight/density* and *air/nothing*.[6] The principles that pick out material entities and guide reasoning about them for preschool children include the principle that a given region of space can be occupied by only one portion of matter at a time (the continuity principle), the principle that material entities are publicly observable, and the principle that material entities interact causally with each other (the contact principle). Unlike adults, the young child does not take weight to be a core property of matter. This is seen by the judgment that heat, light, and electricity are "made of some kind stuff," just like cars, trees, and animals and unlike ideas and dreams. More strikingly, weight is viewed as an accidental property of prototypical material entities. For example, most children up through age 10 judge that a pea-sized piece of styrofoam, although material, weighs nothing at all. Weight therefore is not a necessary property of entities judged material.

Because weight is not a necessary property of material entities, it cannot provide a measure of amount of matter. Like the Greeks (Jammer, 1961), young children have no measure of matter (Piaget & Inhelder, 1941; Carey, 1991). For young children, weight (an extensive magnitude) is not differentiated from density (an intensive magnitude) and therefore cannot be an extensive property of matter (Carey, 1991; Smith, Carey, & Wiser, 1985). Children know that if object A weighs 250 grams and if object B weighs less than A, then object B will weigh less than 250 grams. But the same children are perfectly happy to judge that object A can be broken into 10 pieces, each of which weighs 0 grams!

Finally, preschool children, and roughly half of our sample of 6- to 10-year-olds, have not constructed a model of matter as continuous and homogeneous. Asked to imagine cutting a piece of steel in half repeatedly, they claim one finally will arrive at a piece that is so small that it no longer occupies space, and also that one will arrive at a piece of steel in which one could (in principle) see all the steel: There would be no more steel inside. The other half of the elementary schoolchildren, and all the 12-year-olds, judged that steel is continuous, homogeneous, and infinitely divisible: No matter how small the piece, it would still occupy space and would have more steel inside it. (By age 12, in spite of science education, most children have constructed a continuous model of matter.) The continuous model of matter supports the distinction between weight and density, providing the possibility that weight may become one of the core properties of material entities.

How do children come to reconceptualize matter and material objects? Mappings between the domains of physics and number, constructed through the processes described by Nersessian, appear to play a role in this process. Carol Smith and her collaborators (e.g., Smith, Snir, & Grosslight, 1992; Smith, Grosslight, Macklin, & Davis, 1993) have explored the use of physical analogies to drive 11- to 13-year-olds' reconceptualization of matter, especially the differentiation of weight from density and the construction of weight as an extensive quantity. The ideas are tested in the arena of science education. The curriculum that Smith et al. have developed centers around computer-implemented, interactive visual models that serve to represent the mathematics of intensive and extensive quantities. For example, in one model, weight is represented by the number of dots, volume by the number of boxes of a fixed size, and density by the number of dots per box. Students first work with the models, exploring the mathematical relations between the extensive and intensive quantities internal to the models. Then students work on mapping the models to the material world, by exploring such phenomena as the constant ratios of size to weight within each material and the laws of floating and sinking. This mapping is slow and difficult: Without having differentiated weight from density, students cannot readily succeed in mapping number of dots per box to density, rather than to absolute weight or to some other physical variable.

To facilitate this mapping, Smith et al. use the physical analogy of dissolving sugar in water as a source domain (in which sweetness is the intensive quantity and amounts of sugar and water are the extensive quantities) as well as the visual model of the intensive quantity (dot crowdedness). The visual model embodies the mathematics of extensive and intensive quantities and serves as a bridge between mathematical representations and the target domain. As did Maxwell, students explore the analogy in a piecemeal manner, over time. When they encounter the phenomenon of thermal expansion and attempt to model it, they must change the model (material kinds do not have constant densities). This process consolidates and extends their understanding of the mathematics of intensive and extensive quantities, and it contributes to change in their concept of matter. It results in a mapping between physics and mathematics that gives rise to a new core concept: *quantity of matter*.

Smith et al. also employ thought experiments and limiting case analyses in their curricular intervention. Here we provide one example of a limiting case analysis (concretely exemplified rather than part of a thought experiment). Students who lack an extensive concept of weight maintain that a single grain of rice weighs nothing at all. As a classroom exercise, teams of students discover how many grains of rice placed on one edge of a playing card balanced on a thick fulcrum cause it to topple (around 50). They are asked to explain why the card fell. (Most say, "the rice was heavy.") Then the playing card is balanced on a thinner fulcrum, such that 10 grains of rice suffice, and again students explain that the rice was heavy enough to topple the card. Then the card is balanced on a very very thin fulcrum, and a single grain of rice placed on its edge causes it to fall. Students are asked to reconsider whether a single grain of rice weighs a tiny amount or nothing at all. Seven-year-olds are unmoved by this experience; they insist that the single grain of rice weighs nothing. A classroom of 10- or 11-year-olds presents a completely different picture. First, they are very interested in the experiment, and a lively discussion ensues, pitting those who now think that a grain of rice weighs a tiny amount against those who still maintain it weighs nothing. In every class observed thus far, the proponents of the former view have spontaneously produced two arguments: (1) a sensitivity of the measuring device argument and (2) the argument that a single grain of rice must weigh something, because if it weighed 0 grams, then 50 grains of rice would weigh 0 grams as well.

Note that these two arguments depend on the mapping from physical objects to number: It is only in the realm of mathematics that repeated division of a positive quantity always yields a positive quantity, and that repeated addition of 0 always yields 0. In the realm of physics, in contrast, every physical interaction has a threshold. Repeated division of an object always results, eventually, in objects that are too small to be detected by any given physical device. Moreover, a collection of objects, each of which falls below the threshold of a given device, may well be detectable by the device. Like the Aristotelian physicists discussed by Jammer (1961, see note 3), 7-year-old children who resist Smith's limiting case analysis and continue to insist that a single grain of rice weighs nothing are not necessarily irrational. Rather, they may be reasoning consistently within the domain of perceivable objects and outside the domain of number. Smith's limiting case analysis forms part of the process of constructing a mapping between weight and number and fosters the development of an extensive concept of weight. It does not, however, guarantee that the mapping will be constructed and used.

Smith et al. (1993) recently documented that their model-based curriculum, including thought experiments and limiting case analyses, is more effective in inducing conceptual change than is a control curriculum that does not involve these heuristics. Wiser (1988) has obtained similar results from the use of physical analogy in inducing conceptual change in high school students' thermal concepts, especially the differentiation of heat and temperature.

These results support Duhem's and Nersessian's proposals concerning the mechanisms effecting conceptual change. In addition, they reveal that metaconceptually unsophisticated individuals, who are not part of the social process of scientific theory building, can use the heuristics that scientists use to effect conceptual change. The success of these curricula suggests that conceptual change in childhood is the same sort of process as is conceptual change in the history of science. Studies of conceptual change in physics provide evidence against the strong universality hypothesis.

As in the case of number and psychology, however, the weak universality hypothesis is left untouched. Smith's students did not spontaneously explore the mapping between number and weight, and they did not invent the physical analogy, the thought experiments, or the limiting case analyses. These were constructed to be instructional aids by adults who understood the students' conceptions of matter and who knew what conceptual change they wanted to effect. This demonstration therefore leaves open the possibility that only metaconceptually aware theory builders invent thought experiments, limiting case analyses, and physical analogies in order to construct and use mappings between different knowledge domains.

In summary, studies of conceptual change in childhood show the strong universality hypothesis to be false. Children and adults, like scientists, can bring about changes in their core, domain-specific systems of knowledge by constructing and using mappings across those systems. These studies weaken the expectation of cross-cultural cognitive universals, even in domains supported by innate principles. The personal qualities of mature scientists and the cultural institutions of science are not necessary for conceptual change. Psychologists and anthropologists therefore cannot expect that intuitive theories held by lay people the world over will be enriched versions of the innate principles in these domains.

Conclusions

Studies of conceptual change, both in the history of science and in childhood, suggest that human reasoners go beyond the principles at the core of their initial systems of knowledge. Reasoners do this, in part, by constructing mappings across different knowledge domains. Because the possibilities for mapping across different domains of knowledge are vast, there is little reason to expect, a priori, that all adults in all cultures will have commensurable conceptions, even in those domains where humans are endowed with systems of knowledge whose principles both determine the entities of the domain and support reasoning about those entities.

Still, we do not know whether children or adults spontaneously construct mappings across domains, by means of such heuristics as those described above, in the process of developing systems of culturally constructed knowledge. In the absence of developed science, does cognitive development in all cultures require conceptual change, such that the conceptual systems of the members of distinct cultures are incommensurable with the innately given systems? And does the cultural construction of knowledge in these domains lead to intuitive theories across different cultures that are incommensurable with each other? We offer these two related questions as *the* central problems for cognitive anthropology. At least they are the questions we would most like to have answered.

Notes

1. Some researchers take the wide-ranging changes, at about age 4, in children's abilities to reason about false beliefs, about the appearance–reality distinction, and about certain perspective-taking tasks as evidence for conceptual change in the child's theory of mind (e.g., Perner, 1991). Others maintain that the mature psychological conception of a person is an enriched version of the 2-year-old's conception (e.g., Wellman, 1990; Fodor, 1992). We do not take sides in this debate but note that researchers on both sides hold that the child, even the baby, attributes to people the capacity for self-generated action, for contingent reactions to the baby's own reactions, and for attention to entities in the world. The later development of representational theories of mind would appear to preserve this core conception of people as sentient and purposive beings.

2. Competing views of analogical reasoning within cognitive science (e.g., Gentner, 1989; Holyoak & Thagard, 1989; Carbonell, 1986) flesh out the details of how such mappings are constructed and used.
3. Galileo's thought experiment reveals that the Aristotelian concept of *weight* is undifferentiated between an extensive quantity (the weight of the composite object is additive) and an intensive quantity (the weight of the composite object is an average). According to Jammer (1961), Aristotle's concept of weight was in fact undifferentiated in this way. Indeed, Aristotle considered a version of Galileo's thought experiment and drew the conclusion that the composite object would fall faster, because the weight of any given piece of substance was a function of the totality of which it was part: Both the small and the large object would be heavier when they became part of a single object! Galileo's thought experiment therefore leads to no contradiction within Aristotelian physics. Thought experiments, like any experiments, depend upon current conceptualizations and do not guarantee conceptual change.
4. This deepening continues beyond age 10; ten-year-olds judge that a skunk, accidentally given an injection of a chemical shortly after birth, which caused it to grow into an animal that looks just like a raccoon, has indeed become a raccoon; adults judge it will continue to be a skunk (Keil, 1989).
5. Springer and Keil (1989) offer no analysis of what constitutes a "biological" functional consequence and include such examples as "has stretched out eyes which make it easier to see their enemies."
6. For example, all 4-year-olds and roughly half of the 6-to 10-year-olds maintained that the box mentioned here could contain both the steel block and an equal volume of air at the same time, "because air isn't anything." The same children also asserted that we need air to breathe, that the wind is made of air, that there is no air in outer space or on the moon. In a different interview of 6-year-olds, in which air had not been mentioned, about one quarter of the children posited air as the material of which dreams and ideas are made!

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