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SCIENCE AND CORE KNOWLEDGE*

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While endorsing Gopnik's proposal that studies of the emergence and modification of scientific theories and studies of cognitive development in children are mutually illuminating, we offer a different picture of the beginning points of cognitive development from Gopnik's picture of "theories all the way down." Human infants are endowed with several distinct core systems of knowledge which are theory-like in some, but not all, important ways. The existence of these core systems of knowledge has implications for the joint research program between philosophers and psychologists that Gopnik advocates and we endorse. A few lessons already gained from this program of research are sketched.

1. Introduction. Are studies of the emergence and modification of scientific theories and studies of cognitive development in children mutually illuminating? Gopnik argues that they are, because cognitive development in children is driven by the same processes of constructing, revising, and replacing theories as those at work in scientists. Gopnik's argument, if right, has significant implications for practitioners both of cognitive science and of philosophy of science. Cognitive scientists would have to accept that they face the same difficult analytic challenges as do historians of science, such as distinguishing between incremental acquisition of knowledge, on the one hand, and conceptual change, on the other, and understanding how genuinely new concepts emerge. And philosophers would have to accept that many age-old problems about theory change and the origin of concepts are amenable to new avenues of empirical study. Indeed, the developing child might provide a particularly illuminating case study of theory development and theory change, revealing the central cog-

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nitive processes of human beings (including scientists) freed from the wealth of specific knowledge, methods of data collection and analysis, and traditions that clutter any actual scientific enterprise.

For analogies between the child and the scientist to be fruitful, however, one must specify what aspects of cognitive development depend on the emergence of, or change in, intuitive theories. Clearly, not all children's knowledge stems from theories and not all changes in knowledge and performance depend upon theory change. Most developmentalists would agree that the cognitive resources of the child include many structures that are not usefully categorized as theories, such as schemas, scripts, lists, prototypes, and other representations that arise and change during cognitive development. Children learn the course of events in a restaurant, the prototype of an elephant, and the sequence of the alphabet, for example, and these achievements must be distinguished somehow from processes of theory construction and revision. Moreover, most developmentalists would agree that a variety of mechanisms produce cognitive changes in children. Maturational processes, for example, yield increases in representational, memory, and attentional capacity, and in executive function, and all of these increases have an impact on children's cognitive functioning. Parameter setting mechanisms appear to play a role in language acquisition. If a theory of cognitive development must admit representational structures that are not theories and engines of cognitive development that are not processes subserving theory change, then the research program Gopnik advocates requires developing the analytic and empirical tools for establishing what is, and what is not, an instance of theory change.

Most important, some of the cognitive achievements of children and adults do not result from processes of theory change, we believe, because they do not result from changes of any kind: they depend on core cognitive systems that emerge early in development and remain constant thereafter. Indeed, core knowledge systems may underlie the very phenomena on which Gopnik focuses. In our commentary, we sketch a picture of early cognitive development which gives pride of place to these core knowledge systems and we discuss implications of this picture for the collaborative research project Gopnik advocates. We focus on the "theories all the way down" aspect of Gopnik's view. In contrast to Gopnik, we suggest that children's initial cognitive endowment consists of a set of innate core systems of knowledge which have some, but not all, of the properties of later developing intuitive theories and scientific theories. Most importantly, the mechanisms by which these core systems arise during early development are distinct from those that underlie theory construction later in childhood and in the history of science. If we are right, then the study of initial knowledge does not directly illuminate of the processes of knowledge development in science. We conclude by suggesting where one should pursue the analogy between child and scientist and we offer a few lessons that have already been learned, we believe, in the course of such work.

2. Core Knowledge. There are two very different views of cognition and its relations to knowledge acquisition: 1) human cognition depends on a single, general-purpose, theory-forming capacity; and 2) human cognition builds on a set of domain-specific systems of knowledge (see Carey and Gelman 1991, Hirschfeld and Gelman 1994). The domain-specificity view emphasizes the links between cognition in humans and in other animals, and the links between cognition, perception, and action. As is often noted, the highest cognitive feats of animals, such as the dance of the bees, the web of the spider, the songs of birds, and the alarm calls of monkeys, are not the products of a general-purpose intelligence, but of domain-specific, task-specific cognitive systems. Similarly, the perceptual and action capacities of humans result not from one general-purpose system for perceiving or acting, but from the orchestration of distinct, specialized systems for perceiving different kinds of environmental properties (e.g., color, depth, melodies, etc.) and for engaging in different patterns of activity (e.g., reaching, grasping, locomoting, scanning a scene). Studies of early cognitive development suggest to us that human cognition is built upon structures that are just as specific as those that underlie animal cognition, human perception, and human action. Just as humans are endowed with multiple, specialized perceptual systems, so we are endowed with multiple systems for representing and reasoning about entities of different kinds.

These studies suggest that there are at least four core conceptual systems encompassing knowledge of objects, agents, number, and space. Each system of knowledge applies to a distinct set of objects and phenomena. For example, knowledge of physical objects applies to the behavior of material bodies, and knowledge of agents applies to the actions of people and animals. More deeply, each knowledge system is organized around a distinct set of basic principles which enable infants to identify the entities in the domain and constrain reasoning about those entities. These early-developing, domain-specific, and task-specific systems of knowledge allow infants to solve a host of immediate and pressing problems without having to test out a large space of possible solutions in advance.

Consider infants' representations of physical objects. By 4 months of age, infants represent the boundaries, internal connectedness, and occluded positions and motions of objects in accord with three spatiotemporal constraints on objects' behavior: objects move cohesively (maintaining their connectedness and boundaries), continuously (without jumping from one place to another or passing through other objects), and on contact with other objects (distinct objects do not interact at a distance; see

Spelke and Van de Walle 1993). From a very early age, these principles guide infants' inferences about hidden events. For some flavor of the evidence in favor of these claims, consider the following phenomenon suggesting that 6-month-olds' reasoning about the motion of objects is guided by the principle of contact. If infants of this age see one object roll behind a screen toward a partially visible, stationary object, which then begins to move in the same direction, they infer that the first object hit the second one. This inference is shown by their increased looking time (a reaction to novel or unexpected events) if the screen is removed to reveal an event where the first object stops short of the second before the second goes into motion (Ball 1973, Spelke et al. 1995; see Kotovsky and Baillargeon 1994 for evidence of this effect at 3 months, and see Baillargeon 1993, 1994, for reviews of many further studies showing that infants under 3 months represent hidden objects and make inferences about their hidden motions).

Are the systems of knowledge that underlie these inferences like the theories of scientists? If, as Gopnik indicates, a theory is at heart a representational structure that embodies causal notions, licenses distinct types of explanations, supports distinct systems of predictions, and reflects basic ontological commitments, then, *contra* Gopnik, research on infants leaves this question supremely open. Further, young infants' knowledge structures differ from later developing intuitive theories and scientific theories in four salient respects.

First, the means by which scientists identify the entities in the domain of a theory are highly indirect and are often dependent upon technology that is deeply theory-laden (e.g., cloud chambers, chemical tests, spectral analysis, balance scales). In contrast, the principles that determine and guide reasoning about the entities in core systems can be read off spatiotemporal analyses of perceptual input. The inferences infants make about hidden objects (e.g., permanence, contact causality) have the same informational content as the output of spatiotemporal analysis of the perceptual array. For example, infants, like adults, perceive mechanical causality directly when the spatiotemporal conditions for Michotte's launching events are met (Michotte 1963, Leslie 1988, Oakes 1994), and it is exactly this sort of contact causality that is inferred in the hidden events of the Ball studies cited above (Ball 1973, Spelke et al. 1995). For another example, infants and adults analyze self-generated motion and patterns of contingent reaction between entities as evidence for intentional, goal directed action (Gergely et al. 1995, Watson 1979). This one-step relation between spatiotemporal analysis as input and conceptual output is not generally true of later developing theories, intuitive or scientific.

Second, the capacity for constructing and understanding scientific theories surely is uniquely human. In contrast, all the evidence currently available suggests that the four core cognitive systems found in human infants are shared by other animals (see Hauser and Carey (in press) for evidence that infants and primates represent and reason similarly about objects, numbers, and intentional agents; see Hermer and Spelke (in press) for evidence that young children and other mammals construct similar representations of space; see Gallistel 1990 for an extensive review of evidence for animal representations of number and space). Consider again the example of object representation. Recent research has investigated the object representations of 2-day-old chicks, presenting chicks with visual displays very similar to those used in studies of human infants. Like their human counterparts, chicks have been found to perceive the complete shapes of partly hidden objects and the existence and location of fully hidden ones (Regolin and Vallortigara 1995; Regolin, Vallortigara, and Zanforlin 1995), and their object representations have been found to depend primarily on an analysis of spatiotemporal relationships revealed over object motion (Regolin and Vallortigara 1995, O'Reilly and Johnson 1994). These findings suggest that early developing cognitive systems in humans have a long evolutionary history. We note, by contrast, that such homologies between human and animal representations have not been found for children's later developing theories such as intuitive biology, matter, or cosmology.

Third, theories are central knowledge systems widely available to guide reasoning and action. In contrast, the early expression of core knowledge systems is response- and task-specific. For example, some of the spatiotemporal analyses which allow infants to predict the future position of an object that moves from view do not serve as a guide to predictive reaching for the same moving object, and some of the principles guiding predictive reaching do not serve as a guide for extrapolating occluded object motion (see Spelke, von Hofsten, and Vishton 1994). The systems of object representation guiding perception *vs.* action continue to be distinct in adults (Milner and Goodale 1995), providing further evidence for task-specific core knowledge systems.

Fourth, theories are always open to revision, including radical revision involving conceptual change or even abandonment. Core systems, in contrast, are elaborated but not revised: neither infants, nor children, nor adults engaged in commonsense reasoning ever give up their initial systems of knowledge. Of course, much knowledge is never revised during development (that the sun is high at noon, or that "b" comes before "c" in the English alphabet.) But core cognitive systems remain not only when they give rise to beliefs that are true and useful, but also when they do not. For example, the infant's representations of objects as cohesive, moving on spatiotemporally continuous paths, and subject to contact causality continue to exist in adults and are not supplanted by later learning, even by learning classical and quantum mechanical theories that directly contradict them (e.g., see Proffitt and Guilden 1990). Although infants learn many new facts about the behavior of objects, their newly gained knowledge enriches core knowledge without overturning it.

The core system view shares much with Gopnik's view, but differs from it in critical ways. Like Gopnik's initial theories, core systems are conceptual and provide a foundation for the growth of knowledge. Unlike later developing theories, however, core systems are largely innate, encapsulated, and unchanging, arising from phylogenetically old systems built upon the output of innate perceptual analyzers. These differences make it unlikely that the development of core systems engage the same processes as the development of intuitive theories in childhood or the development of scientific theories in the history of science.

3. Why the Distinction between Core Knowledge and Later Developing Theories Matters. In her writings (both the article under discussion here and Gopnik and Meltzof in press), Gopnik develops two examples of cognitive development which she treats as examples of theory change: developments within the concept of *object* during infancy and developments within the theory of mind during the early preschool years. We think it likely that both the concept of *object* and the concept *intentional agent* are embedded in core systems of knowledge, and that development in each case depends on a mix of enrichment and maturation. If we are right, then philosophers seeking lessons about theory change in science from case studies of cognitive development should not look here.

3.1 The object *concept.* Some of the most robustly replicated phenomena within developmental psychology have been interpreted to reflect conceptual change within the concept of *object*. If infants below age 7 months are reaching for an object that is placed behind or beneath a barrier, they cease reaching, as if they no longer believed that the object exists (Piaget 1954). Even after infants succeed on this basic task, they make what has been come to be called the "A-not B error." After successfully retrieving an object hidden at place A, infants who see an object hidden at place B look again at A rather than B, as if they have learned an empirical generalization, "look where you have found things before," and are not tracing the path of an enduring object (Piaget 1954, Wellman, Cross, and Bartsch 1987). Phenomena such as these have been taken to show that our everyday theory of the world as composed of objects that exist permanently, independently of our actions, is constructed slowly during the first two years of infancy.

Gopnik believes that these developmental changes are instances of theory change, analogous to Darwin's construction of the natural selection theory of evolution. We do not. As we have already indicated, there is overwhelming evidence for object permanence as young as 2 months of age in human infants (e.g., Baillargeon 1995) and 2 days of age in chicks (Regolin et al. 1995). For a flavor of the evidence that human infants are committed to object permanence, and (more strongly) to the principle of continuity (objects exist continuously and move on connected paths, whether visible or occluded), consider the following phenomenon: two screens are placed on a stage, and the infant sees one object emerge from the left of the left hand screen and then return behind it, followed by a physically identical object emerging from the right of the right hand screen and then returning behind it. The object motion is consistent with one object going back and forth behind the two screens, except no object is ever observed in the space between the screens. Adults, guided by the principle of continuity, infer there must be at least two objects involved in this event, one behind each screen. So do 2½-month-old infants, who show a novelty reaction if the screens are removed and only one object is revealed behind them (Aguiar and Baillargeon 1996; for converging evidence, see Rochat and Hespos 1996, Spelke et al. 1995, Wilcox, Rosser. and Nadel 1994, Wynn 1992, Xu and Carey 1996).

Of course, those of us who believe that the Piagetian phenomena do not reflect a different concept of *object* than that of adults owe an account of why infants fail to reach for hidden objects or commit A/not B errors. Although it is beyond the scope of this commentary to discuss the many alternative interpretations of these errors, we note that the extensive literature on this phenomenon suggests that developmental changes in object search have more to do with the development of action than with the development of object representation. In particular, children have been found to engage in A/not B search patterns not only when an object is hidden but when an object is visible (Harris 1974) or when they view motions of covers over potential hiding places containing no hidden object at all (Smith and Thelen 1995). Further, there is evidence that developmental changes in search patterns primarily depend on maturational changes in the brain structures subserving executive function, which permit means/end planning and inhibition of competing responses (Diamond 1991).

One source of evidence that casts doubt on the theory construction view of the development of object search is the robust finding that the developmental progressions so consistently observed in human infancy between the ages 6 and 18 months also are observed during primate development (Antinucci 1989). For example, Diamond (1988, 1990, 1991) has shown that the developmental changes involving the A/notB errors of infants of 7 months and beyond, are mirrored, in parametric detail, by identical changes in 2- to 4-month old rhesus monkey infants. It is known that these latter changes are driven by maturation of frontal cortex (Goldman-Rakic

1987). Similar changes may occur at much younger ages in chicks, a still more precocial species (Regolin, pers. comm.). If such changes show an important analogy between the scientist and the child, they also show an important analogy between the scientist and the monkey or between the scientist and the chick. However, we think it unlikely that the chick's or the monkey's emerging abilities to search for occluded objects bear much relation to emerging scientific theories, e.g., to the processes underlying Darwin's construction of the theory of natural selection.

3.2 Theory of Mind. The extended example of Gopnik's paper is the development of the theory of mind. Although the phenomena that mark the transition from 3- to 4-year-olds' reasoning about their own and others' actions are not in question, the interpretation of these phenomena is a much debated topic in cognitive science. Many have suggested that theory of mind is the product of a core knowledge system (see Leslie 1994, Fodor 1992, Sperber 1994), and several considerations favor this account. First, theory of mind reasoning has clear precursors in infants, who represent human actions as goal-directed (Gergely et al. 1994, Woodward 1996) and as guided by perception (e.g., Baldwin and Moses 1994). Moreover, the 4-year-old's system of knowledge of mind would seem to be a (considerably) enriched version of the infant's system, not a radical overturning of it. Theory of mind thus appears to depend on an early-developing (possibly innate) system of knowledge that is elaborated over development, as are other core knowledge systems. Second, theory of mind reasoning shows response specificity: 2-year-old children who fail theory of mind tasks in which they must verbally predict what a given character will do or say may succeed at implicit versions of these tasks, in which they watch a series of events and anticipate (with eye movements or other behaviors) what a character will do next (Clements and Perner 1994). Response-specificity, we have noted, is another hallmark of core knowledge systems. Third, neuropsychological evidence suggests there are developmental disorders such as autism, in which development of theory of mind is selectively impaired (Baron-Cohen 1993), and Williams Syndrome, in which it is selectively spared (Karmiloff-Smith et al. 1995, Tager-Flusberg 1994). The pattern of abilities and impairments in Williams Syndrome pose particular difficulties for Gopnik's analysis of theory of mind. Children with Williams Syndrome begin to reason about beliefs, desires, and human actions at about normal ages (Tager-Flusberg 1994), yet even adolescents and adults appear to be unable to undergo any of the forms of conceptual change associated with theory building (Johnson and Carey 1996). Domain-specific cognitive impairments are puzzling if one views the impaired abilities as products of a single, general theory-building capacity, but they are to be expected if those abilities depend on domain-specific, core systems of knowledge.

4. Where We Agree. In spite of the above disagreements, we have broad sympathy for the research program Gopnik advocates. We agree that the self-conscious, formal, social setting of developed science is no barrier to fruitful analogies between intuitive theories and scientific theories (see Carey and Spelke 1994). We believe there is a deep analogy between cognitive development in children and in science in several well studied cases, although the cases we find convincing occur later in childhood than Gopnik's examples: intuitive biology in the years 4 to 10 (Carey 1985, 1988, 1995; Hatano and Inagaki 1994; Keil 1989, 1992, 1994), intuitive theory of matter in the years 6 to 12 (Carey 1991, Inhelder and Piaget 1941, Smith, Carey, and Wiser 1985), intuitive cosmology (Vosniadu and Brauer 1992), intuitive mathematics in elementary school children as they construct concepts of 0, infinity, negative numbers, and fractions (Gelman 1991), and intuitive theories of thermal phenomena and mechanics in adolescents who study physics (e.g., Carey 1986, Clement 1982, Wiser 1988b). In the remaining pages of our commentary, we sketch some lessons from this literature concerning both the challenges and the promise of the research program we and Gopnik endorse.

4.1 Lesson I: Accretionism and Conceptual Change. The literature on cognitive development underlines the importance of distinguishing knowledge acquisition which involves enrichment of an existing conceptual base, on the one hand, and the acquisition of new concepts that depend on, and produce, knowledge restructuring. (By identifying cognitive development with theory change, Gopnik sometimes seems to blur this distinction, but we expect that she would agree that it can and must be made.) Those who endorse the existence of conceptual change hold that in at least some cases of theory change, some core concepts of the new theory (T2) cannot be expressed in terms of the original theory (T1) and vice versa (Carey 1988, 1991; Hacking 1993; Kitcher 1988; Kuhn 1982). The nature, or even coherence, of the distinction between conceptual change and knowledge enrichment has been a source of debate ever since the seminal work of Kuhn (1962) and Feyerabend (1962; see Suppe 1977, Davidson 1979). Nevertheless, research on cognitive development supports the need for such a distinction, contributes to the analysis of it, and provides the groundwork for studies of the mechanisms of conceptual change.

Conceptual changes in the history of science and in cognitive development take several forms. Perhaps the most common form is differentiation, in which the undifferentiated parent concept from T1 no longer plays any role in T2. Examples include Galileo's differentiation of *average* from *instantaneous velocity* (Kuhn 1977), Black's differentiation of *heat* from *temperature* (Wiser and Carey 1983), and the child's differentiation of *weight* from *density* (Smith, Carey, and Wiser 1985, Carey 1991). Another common form of conceptual change is the coalescence, in T2, of concepts which were considered fundamentally different kinds in T1. Examples include Galileo's abandonment of the Aristotelian distinction between *natural* and *artificial motion* (Kuhn 1977) and the child's uniting of *animal* and *plant* under the new concept, *living thing* (Carey 1985). Other forms of conceptual change involve the reanalysis of a concept's basic structure, such as the Newtonian reanalysis of *weight* as a relationship between objects rather than a property of objects, or the child's reanalysis of *number* as those entities that participate in, and result from, the operations of addition, subtraction, multiplication, and division, rather than those entities that participate in, and result from, verbal counting (Gelman 1991). A final form of conceptual change rests on the analysis of concepts as having a core/periphery structure and involves changes in a concept's core structure, as when children come to explain object solidity in terms of properties of matter rather than properties of objects themselves (Carey 1991). Carey (1988, 1991) discusses each of these types of conceptual change as they occur in children's cognitive development.

We are not claiming that the difference between knowledge enrichment and conceptual change is sharp, for there are a variety of intermediate cases. Moreover, we do not believe, with Kuhn (1962) and Feyerabend (1962), that theories before and after conceptual change are radically incommensurable (see Carey 1985, 1991; Kitcher 1988; Kuhn 1982; Hacking 1993). Rather, the case studies of cognitive development enumerated above suggest that children's earlier and later theories bear the relation that Kuhn (1982) called "local incommensurability." Because not all children's concepts undergo change, the unchanging parts of their theories serve as frameworks for those that do (just as in the case of historical development of concepts; Kuhn 1982; Kitcher 1988; Henderson 1989).

Consider, for example, the changes within the ontologically central concepts *person* and *animal* between ages 4 and 10. Young infants and preschoolers have an elaborate concept *person*, the prototypical agent, as the literature already cited attests (for reviews, see Spelke, Phillips, and Woodward 1995, Leslie 1994, Wellman and Gelman 1992). Young children also conceive of animals as agents, distinguish kinds of animals, and accumulate extensive knowledge about different kinds of animals (Carey 1985, Mandler, Bauer, and McDonough 1991, Wellman and Gelman, 1992). Nevertheless, there is ample evidence that the preschooler's concepts *animal* and *person* differ from the 10-year-old's and are embedded in very different intuitive theories (Carey 1985, 1988, 1994). According to one analysis (Carey 1985), the core of the preschooler's concept *animal* is that of a behaving being: indeed, animals for children of this age are fundamentally deficient variants of the prototypical behaving beings, people. The young child understands and interprets the body in terms of the role body parts play in supporting behavior. That is, the preschooler's framework theory (T1) in which the concepts *person* and *animal* are embedded is a theory of mind or intuitive psychology rather than an intuitive biology. By age 10 or perhaps earlier, the child has constructed a new intuitive theory of biology (T2), with *animal* and *plant* coalesced into the single ontological kind *living thing* (Carey 1985, Keil 1979) organized around the life cycle and the function of body parts in the service of maintaining life (see Carey 1995 for discussion). This new theory has been variously characterized as a vitalist biology (Hatano and Inagaki 1994) and as the container theory of the body (Crider,1981). It is a new framework theory T2, an intuitive biology organized around the concept of the life cycle of organisms and a view of bodily function as maintaining life.

These changes within the concepts *person* and *animal* require changes in a host of interrelated concepts. Related conceptual changes include the differentiation of the preschooler's concept *not alive* into the adult's concepts *dead, inanimate, unreal*, and *nonexistent* (Carey 1985, 1988; Laurendeau and Pinard 1962; Piaget 1929) and the differentiation of the child's concept *family* into separate concepts *biological family* and *social family* (Solomon et al. 1996). Other conceptual changes include the reanalysis of *death* from a behavioral interpretation to include the collapse of the bodily machine (Carey 1985; Koocher 1974; Nagy 1948, 1953), and the reanalysis of *baby* from small, helpless animal to reproductive offspring (Carey 1985, 1988; Callanan 1995; Solomon et al. 1996). The core features of the concept *species* shift away from physical characteristics toward origins of the animal (Keil 1989, Johnson 1994). Finally, the concept *person* is reanalyzed from prototypical behaving being to *one-animal-among-many* (Carey 1985).

The above characterization of conceptual change within intuitive biology is supported by a varied array of empirical findings, from the spontaneous questions children ask, to analyses of children's patterns of predictions and inductive inferences, to the explanations children give for what are, for adults, biological phenomena. Perhaps most convincing are cases where children's concepts trap them in contradictions that they cannot resolve. For example, Carey (1985) analyzes a 4-year-old's worries about how it is that statues are not alive, yet we can still see them, as reflecting the undifferentiated concept *dead/inanimate/nonexistent*. The Florentine Experimenters' undifferentiated concept *heat/temperature* trapped them in comparable contradictions that they recognized but could not resolve (Wiser and Carey 1983, Carey 1991).

The above characterization of conceptual change between the preschool child's T1 of animals, people, and plants, on the one hand, and the 7- to 10-year-old's T2 is supported by a case study of abnormal development in people with Williams Syndrome, a rare form of mental retardation which spares many linguistic abilities in the face of impaired analytic and metaconceptual skills (Johnson and Carey 1996). Ten adolescents and adults with this syndrome were found to have extensive encyclopedic factual knowledge of animals (e.g., the distribution of bodily characteristics across the vertebrate/invertebrate distinction), a state of knowledge typical of young adolescents with verbal mental ages of 11. However none of the ten subjects had undergone the conceptual reorganization described above; none had constructed T2. Their factual knowledge was still organized in accord with the theoretical life concepts of preschool children (T1). The dissociation, in Williams Syndrome, between knowledge enrichment and conceptual change underscores the distinction between these two types of knowledge acquisition.

4.2 Lesson II: Mechanisms Underlying Conceptual Change. Although case studies in the history of science and in cognitive development provide convincing evidence for the existence of conceptual change, deep questions remain about how such changes take place. Because scientific theories, intuitive theories, and core systems of knowledge all provide principles that enable a reasoner to identify the entities and phenomena in their domains and influence the interpretation of those entities and phenomena, reasoning within any of these systems can turn in a circle. It should be extremely difficult for a person who reasons within the context of one system of knowledge to discover entities and relations beyond that system. If the concepts in T1 are even locally incommensurable with those of T2, a reasoner should have extreme difficult constructing, or even understanding, T2.

Supporting the analogy between intuitive theory building and scientific theory building are reports of children's often startling resistance to changing their theories, even when a new theory is explicitly taught to them and when contradictions within their original theory are made manifest. For example, studies within the cognitive science of science education suggest that the intuitive theory of mechanics that students bring to the task of learning classical mechanics is a version of the impetus theories of the Middle Ages (McCloskey 1983). Even after years of studying formal physics, student understanding is still couched in the concepts of impetus theory rather than Newtonian concepts (e.g., Clement 1982; see Carey 1986 for a review of this literature.) These observations suggest that the theory-based reasoning of students indeed turns in a self-perpetuating circle. Nevertheless, successful theory change does sometimes take place, both in childhood and in science, and, in our view, one of the most important potential payoffs of the research program Gopnik calls for is the possibility of testing proposals concerning the processes resulting in the construction of genuinely new representational systems.

Work on this problem is most advanced within the context of the literature on science education (see, for example, Smith et al. 1988, Wiser 1988a). But here we begin with the earliest case we know of in childhood development—the earliest conceptual change within the domain of number. We have noted that young infants show a variety of abilities to discriminate between arrays of objects that differ in number and to compute the results of simple additions and subtractions on those arrays (see Wynn 1996 for review). This research suggests that infants have a system that represents the exact numerosity of small collections of objects, irrespective of other quantitative properties of the objects such as their size. This system cannot represent the numerosity of larger collections (above 3 or 4), probably because of limits on parallel individuation (Trick and Pylyshyn 1994). The small number system appears to represent an array of two objects as "an object and another object" rather than as "two objects" (Uller et al. 1996). Extensive research on animals (see Gallistel 1990) and some research on young children (e.g., Rodriguez and Spelke in preparation) suggests that infants also have a system for representing approximate numerosity. The approximate system has a much higher (and unknown) upper bound on set size. It does not, however, represent the exact numerosity of these sets, and its representations of the approximate numerosity of collections of objects are not wholly independent of other quantitative properties of the collection such as object size or density (for discussion, see Gallistel 1990, Spelke and Tsivkin in press).

As one would expect, given the domain- and task-specificity of core knowledge systems, these two representations of number initially appear to be quite independent of one another. That is, the infant appears to have no concept number that connects them. From about 2 to 3½ years of age, however, children laboriously learn verbal counting and come to understand both the point of counting procedures and the meanings of count words (Wynn 1990, 1992b). With this understanding, children appear to gain a concept of number that combines the virtues of the two core knowledge systems, allowing the representation of the exact numerosity of sets with no upper bound independent of other quantitative properties of the objects that compose them. It is this new representation that first appears to distinguish the number abilities of human children from those of animals: although animals appear to possess both the exact and the approximate systems found in human infants, only human children (and perhaps animals explicitly tutored in symbolic counting systems) arrive at a system that combines the properties of these two systems (Boysen 1993, Hauser and Carey in press, Matsuzawa 1985, Pepperberg 1987, Rumbaugh and Washburn 1993).

The mechanisms underlying this conceptual change remain to be unraveled, but existing research supports two suggestions about their nature. First, children's new understanding of number appears to result from their construction of a mapping between their two preexisting systems of number representation: the exact system and the approximate system. Second, in this case, the cultural environment of the child (in particular, the language and counting routines she learns) appears to serve as an impetus to connecting these systems together. These suggestions can be generalized: new theories, and their associated domains and concepts, may often arise in children through the culturally guided combination of their preexisting, core systems of knowledge.

Conceptual change in older children, adults, and scientists also may result, in part, from new mappings across systems of understanding: not just mappings across core systems, but across the constructed systems that result from earlier mappings. The application of new geometrical descriptions on the physical world (e.g., Galileo/Einstein), the discovery of new kinds of mapping between physics and number (see Duhem 1949, Nersessian 1992, Wiser 1988a, Smith et al. 1988), may have important things in common with the young child's construction of a new concept of number. In all these cases, people may change their understanding by bringing together the principles that previously defined, and licensed inferences about, distinct sets of entities. By bringing together the principles inherent in distinct knowledge systems, children and adults may construct new systems of knowledge, defining new classes of entities and licensing new patterns of reasoning and explanation. Indeed, it may be this process of bringing distinct knowledge systems together that most distinguishes human cognition from that of animals and the cognitive structures of older children from those of infants.

We are not suggesting that all conceptual change results from combinations of existing systems of knowledge, or even that the ways young children combine the representations delivered by their core knowledge systems are wholly like the ways older children, adults, and scientists combine descriptions and explanations afforded by their current theories (although we view this as a possibility). The first uniquely human theories are constructed from different materials than scientific theories, so they are unlikely to be as like them as are later theories in childhood. We do suggest that processes for combining the representations from domain-specific systems of knowledge provide one potential mechanism of theory development and conceptual change and that studies of young children provide a promising means to study these processes.

4.3 Lesson III: The Unity of Science. In making this suggestion, we may appear to be advocating a view with absurd consequences. The essence of science (and all rational thought) would seem to be its unity: a scientist who seeks to construct a new explanation for some phenomenon may draw for inspiration on anything that he or she knows, irrespective of the domain-specific content of her knowledge. And a scientist seeking to evaluate a new theory holds it to the test of saving all known phenomena, not just those narrowly in its domain. How could the cognitive processes of such a person rest on a set of domain-specific, task-specific, and response-specific autonomous cognitive systems?

We are persuaded that the search for unifying explanations is a central feature of the scientific enterprise. We also believe this search is central to the young child: why else, for example, would 3-year-old children undertake the lengthy and difficult task of connecting together their well functioning large- and small-number systems. Why not allow each system to operate in blissful isolation from the other? Although all human thought ultimately is based on domain- and task-specific cognitive systems, humans have both the ability and the propensity to map these systems to one another so as to arrive at better and more encompassing ways of understanding what goes on around us. These mappings are a source of conceptual change, both in children and scientists. On this view, the unity of thought is best construed as a goal of human reasoning, always present although never perfectly achieved.

If our suggestions are correct, then cognitive scientists and philosophers of science may gain insights into the mechanisms of scientific theory change by considering the mechanisms by which children construct their first uniquely human, theory-like systems of knowledge. In our view, the task of relating conceptual change in children to conceptual change in science imposes a stringent research agenda on the cognitive study of science. First, one needs to study in detail the properties of humans' core, unchanging systems of knowledge as they emerge in infancy, as they function in the intuitive thinking of adults, and as they continue to influence the thinking of scientists. Second, one needs to study in depth the processes by which new theories emerge from these knowledge systems in children, ordinary adults, and scientists. Students of cognitive development have begun to undertake the first task with studies of infants and young children and they have begun to undertake the second task with studies of science education and studies of theory construction among practicing scientists (e.g., Dunbar 1996). Bringing these studies together into a concerted investigation of cognitive change is a central challenge for future research.

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