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Does Folk Science Develop?

Frank C. Keil

All of us are said to have a set of *folk sciences:* intuitive ways of understanding the world in areas such as biology, physical mechanics, and psychology. In addition, these folk sciences are thought to have deep and interesting similarities to the formal sciences. Both are usually described as having coherence and internal consistency, as well as specifying certain foundational or ontological kinds as the critical entities of concern (Carey, 1985; Slaughter & Gopnik, 1996). Folk and formal sciences also have important interrelations through the course of development and education. Thus, children come to appreciate some aspects of formal science as taught to them in the classroom in terms of both changing some of the misconceptions of their folk sciences and better appreciating methods and forms of reasoning used in the formal sciences.

In this chapter, my focus is on the ways in which naïve understandings of the world change in the elementary school years. How is the folk science of a 5-year-old, if there is one at all, different from that of a 10-year-old, or an adult? In what ways do aspects of the formal sciences come to exert influences on folk sciences in developed cultures? I argue that recent research on how we understand the mental representations of concepts and the nature of explanatory understanding also suggest new ways of thinking about what folk science is, how it develops, and how it is related to the more formal sciences. I also argue that without such a new view of what changes, it might seem that not much at all develops in the area of folk scientific understanding.

Traditionally, cognitive development, intuitive theories—and, by implication, the folk sciences—have often been conceived in ways that emphasized the child as an individual trying to make sense of the world on his own. The child is confronted either with natural phenomena or complex artifacts and then deciphers, as best he can, how things work. Cognitive scientists vary considerably in their views of how this process might work, with views ranging from constructivist and information-processing accounts of the child entertaining a series of ever-more-accurate explicit hypotheses to more behaviorist and dynamic systems views of a child acquiring information in a more associative manner than may occur without any explicit hypotheses at all. Some version of these views clearly has merit, because children do learn something about the world around them in terms of grasping its causal patterns; however, a problem with all these developmental accounts arises when one considers the adult end state. When construed as detailed mechanistic models of how the world works, folk science in the vast majority of adults seems to be an abysmal failure. If adults

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are asked to explain how a natural phenomenon (e.g., a heart pumping blood) or a device (e.g., a toilet flushing a substance) works, their explicit "working knowledge" may amount to little more than a few surface features and a very-high-level functional description that restates the phenomenon. We are surprisingly blind to our own ignorance as well, thinking we understand natural science phenomena and devices far better than we do (Keil, 2006; Lawson, 2006; Rozenblit & Keil, 2002). If such mechanistic models are all there is to folk science, then any account of what develops must be very modest. One doesn't need to posit much learning, regardless of the form, if the end state is an adult deeply mired in ignorance.

Perhaps I have exaggerated the end state a bit for most adults. Many of us have occupations, hobbies, or passions that can lead us to acquire deeper mechanistic understanding. An Olympic sailor really does know how every single piece of equipment on her boat works, such that she could probably take every component completely apart and reassemble it flawlessly. However, such islands of mechanistic expertise only serve to highlight how weak our folk sciences are in most respects. The Olympic sailor is likely to be just as ignorant about the operations of flush toilets and human hearts as her neighbor the accountant. It seems that detailed mechanistic knowledge happens on only rare, highly specialized occasions.

What, then, develops with respect to folk science? In the vast majority of areas, are we barely distinguishable from the young child, with only a few slender slivers of expertise in highly focused areas reflecting our jobs or our passions? Perhaps we know an additional mechanistic tidbit here and there, but nothing that would suggest substantial developmental accomplishments. If we are to construe folk science as the presence of explicit "how things work" diagrams in the head, we may be forced to such a conclusion. Perhaps there are extraordinary limits to how much children and adults can go beyond the core concepts that seem to be present in infancy (Carey & Spelke, 1996). In fact, a much richer array of cognitive abilities may develop during the late preschool and the elementary school years; we simply have to characterize them in different terms. An analysis reveals several classes of such abilities that involve major developmental advances in the ability to

- sense the causal density underlying various phenomena;
- see what sorts of causal relations are relevant and irrelevant to a phenomenon;
- extract coarse causal gists from much more complex patterns;
- distinguish some kinds of causal explanations (e.g., precedents) from other kinds (e.g., mechanisms);
- detect circularity in explanations;
- discover pathways to the most helpful experts;
- evaluate the credibility of speakers both in terms of their motivations, their abilities, and their past performance;
- consider where explanations or empirical investigations are likely to be most fallible; and
- know how to construct an ad hoc explanation on the fly using information that is on hand (even if the ability to retain such explanations is minimal).

If one considers all of these abilities to be part of folk science, then the developmental story is very rich indeed. Moreover, if one acknowledges that an enormous amount of what the child learns is second- or *n*th-hand through others, folk science can be construed as involving all the ways in which we learn to rely on information in other minds (Keil, Stein, Webb, Billings, & Rozenblit, 2008). In the next section, I briefly explore some of these to get a better sense of what develops.

Understanding the Limits of Scientific Methods

One of the pioneers in characterizing these alternative ways of thinking about what develops with respect to folk science is David Klahr. Klahr has repeatedly shown how children come to appreciate something about science as an enterprise in ways that may be largely orthogonal to having a deep mechanistic understanding. Consider, for example, his studies on the emerging understanding of experimental error (Masnick & Klahr, 2003). There is, in fact, a taxonomy of error types in scientific investigations that one must understand to be able to interpret experimental data appropriately. Building on prior work in the philosophy of science, Masnick and Klahr (2003) proposed one such taxonomy with three types of error that can occur during the following five stages of experimentation: of (a) design; (b) physical setup; (c) execution; (d) outcome measurement; and (e) analysis, with the following kinds of errors occurring at some of those stages: (a) design, (b) measurement, and (c) interpretation. Interpretation errors can occur in all stages, with the other error types occurring in one or two stages. In Masnick and Klahr's study, although second and fourth grade children were quite poor at designing unconfounded experiments to explore the properties of a ramp, they nonetheless had quite a good sense of different kinds of errors. Even the second graders were able to distinguish between the different kinds of error when they justified their actions or their conclusions. Errors of interpretation, however, were more difficult for them to understand. In terms of developmental change, the older children seemed to be much more aware of simultaneous errors as a possibility.

The general pattern seems to be one in which even quite young children have some sense of different kinds of error, but it can take several more years before they can simultaneously consider them and then design unconfounded experiments. A more sophisticated understanding of errors and how they interrelate also seems to be linked to increasing causal understanding of the system that one is exploring (Masnick & Klahr, 2003).

In another line of work on a different aspect of understanding the scientific process, Klahr and his colleagues have shown that, whereas 4-year-olds have a great deal of difficulty learning when evidence is indeterminate versus determinate, 5-year-olds are able to learn how to detect indeterminacy after several training trials and then continue to remember how to do so for several months thereafter (Klahr & Chen, 2003; see also Chapter 1, this volume). Younger children do not immediately sense when evidence is indeterminate; they need to be guided toward that inference, but in the early elementary school years they can learn to do so on one task and then show that understanding on analogous tasks.

Klahr (e.g., 2000) has also conducted monumental work on how children discover rules and principles in highly structured, local domains, a kind of knowledge acquisition that does reflect a form of detailed understanding. Just as learning chess or the rules of a complex video game can involve learning an intricate set of rules and procedures, so too can children come to master the rules of a local system, albeit with important limitations and predictable error patterns. When a domain is well structured with a clear set of explicit rules that form a codified set of principles, children can discover them. Their success here is intriguing in light of the great difficulties that everyone exhibits in folk science domains. Although young children can learn intricate sets of rules governing a system, they and even adults have vastly more difficulty naturally learning the principles governing the workings of everyday devices and natural phenomena.

These few examples hardly exhaust the body of work on children's emerging appreciation of the nature of the scientific enterprise. There is a surprisingly complex body of understanding to be mastered, all of which revolves around an increasing understanding of the limits of inquiry methods, both limits intrinsic to those methods and because of the cognitive limits of those engaging in the investigations. One also sees, however, that the young child does not start from scratch. Instead, a rich array of early emerging insights, sometimes present even in preschoolers, helps children get off the ground. This theme recurs in the other areas that I consider in the following sections. There may be some very basic ways that all of us, including young children, sense how understanding may be limited and how to remedy such limitations.

Sensing Causal Patterns Above and Beyond Those of Mechanism

As much as we might think we aspire to clockworks understanding,[1] we rarely succeed. The world of concrete mechanisms is decidedly unkind to our natural cognitive propensities. This is ironic given how often it is assumed that concrete forms of understanding are simpler, easier, and more developmentally primitive than abstract ones. Yet, there are alternative ways to track causal patterns that may be much more natural to human cognition. One of the simplest may be merely noting what kinds of properties are causally relevant to a domain. Colors, for example, tend to be more richly causally connected to natural kinds than they are to artifacts. The color of gold is closely linked to its atomic nature, and the color of many animals helps explain a range of phenomena, from mating habits to adaptations for habitats. In contrast, for most artifacts, color is often

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[1] The term *clockworks understanding* is meant to indicate understanding of causal mechanisms in full detail, that is, in terms of all the causal interactions among all the parts of a system at a foundational level of explanation. For example, a clockworks understanding of a cylinder lock would entail knowing each separable part, its function, and how it interacts causally with all other parts, including hierarchical assemblies. A clockworks understanding of a kidney might occur at multiple levels, ranging from the biochemical to the physical/anatomical, but at any such level would consist of an exhaustive mechanistic account of all components (e.g., cells) and their interactions.

inconsequential. Color is not causally connected to our understandings of chairs, toilets, or helicopters. More generally, there are profiles of the causal relevancy of feature types (e.g., color, surface markings, shape) for various categories (e.g., animals, plants, natural substances, artifacts). Not only do children seem to "know" these profiles, but even some nonhuman primates can sense the differential relevance of color for food as opposed to, for example, tools (Santos, Hauser, & Spelke, 2002). Moreover, children as young as age 5 will use these differential profiles to evaluate explanations offered by others, judging that an alleged expert who emphasizes color, the precise number of parts, and surface markings in an explanation of a novel tool is less likely to know what he is talking about than another expert who emphasizes size, strength, and shape. When children hear experts making similar claims about novel animals or plants, however, they more likely to accept the experts' arguments (Keil, 2010).

Unlike clockworks understandings, which usually seem explicit in nature, children and adults can track causal patterns at other levels without always being consciously aware that they have done so. For example, many adults do not realize that they routinely describe the global purpose or function of objects (e.g., "A hammer is for *x*") but would not do so for natural kinds ("A tiger is for *x*"), even though they describe the functions of parts for both kinds ("A hammer's claws are for *x*," "A tiger's claws are for *x*"). Although it is true that young children will sometimes accept functional descriptions of entire natural kinds (Kelemen, 1999), they nonetheless are more discriminating in their naturalistic patterns of discovery, a behavior close to that explored so extensively by Klahr. For example, when preschoolers are taught to ask questions of a puppet about novel artifacts and animals, they are much more likely to ask what the artifact as a whole is for than they are for animals. In contrast, they ask roughly equally about the purposes of the parts of animals and artifacts (Greif, Kemler-Nelson, Keil, & Gutierrez, 2006). Although most adults are not consciously aware of knowing these distinctions, even preschoolers use them to guide their discovery process.

These kinds of abstract causal expectations are found in preverbal infants as well. It is now well established that preverbal infants have several expectations about inanimate physical objects, for example, that they cannot act on each other at a distance, that they persist when out of sight, and that solids cannot interpenetrate (Baillargeon, 2008; Spelke, Breinlinger, Macomber, & Jacobson, 1992). These expectations, however, might be said to involve concrete representations of objects and their interactions rather than more abstract representations. That view may not be correct given the ways in which infants have expectations about these principles holding for completely novel physical objects and situations; moreover, their reasoning is often described in very general and abstract terms, such as that physical objects will persist in time and space unless certain classes of interventions occur (Baillargeon, 2008). Other situations seem to require even more abstract causal understandings. Consider, for example, the pervasive pattern that intentional agents cause situations to go from disorder to order. When adults see a set of objects become transformed from a disordered collection into an array that is ordered along one or more dimensions (e.g., color, shape, size, kind), they will strongly infer that the change was caused by an intentional agent. By contrast, if an ordered array becomes disordered, adults envision a much wider range of agents, including both intentional agents and completely inanimate ones, such as when a bowling ball knocks over a neatly ordered set of pins.

Adults can become tongue-tied in their attempts to explain why only intentional agents can create order. Their intuition seems to revolve around the idea that agents must have some kind of idealized image in mind that guides their actions, or at least some kind of rule that they use to impose structure on an otherwise-unstructured set of objects. Even this is not strictly correct, because many quite simple organisms can create nonrandom structures, and even chemicals can form highly ordered crystal structures from amorphous liquids, but there is a clear bias in most contexts to expect intentional agents as the forces behind ordering events. These intuitions are also strong in young preschoolers, who are at near-ceiling levels of performance in linking intentional agents exclusively to a wide range of ordering events. These include many events they had never considered before, such as having a randomly arranged set of objects become reordered such that objects of one kind are always in a complementary spatial arrangement with objects of another kind, though even as the full set of complementary pairs is still arranged at random (Keil & Newman, 2008). Despite these extremely consistent and confident judgments, preschoolers are completely unable to explain their judgments. They just know that certain events could be attributed only to intentional agents.

The strength of these preschool intuitions, combined with a striking inability to explain them, suggests that such intuitions might be present in a nonverbal form even earlier. My colleagues and I therefore conducted a series of studies with preverbal infants to determine whether they looked longer at events in which inanimate agents created order than when they created disorder. Such a pattern was found in several distinct studies with infants under 1 year of age (Newman, Keil, Kuhlmeier, & Wynn, 2010). It is very difficult to characterize these infants' understanding in a manner other than a set of highly abstract principles about intentionality, agency, and randomness.

Children are able to use these ways of tracking high-level causal information to get a sense of how knowledge is clustered in the minds of others. Starting in the preschool years (Lutz & Keil, 2002), children are able to infer that phenomena sharing broad causal patterns, such as those governing physical mechanics versus biological functioning, are likely to be understood by the same expert. Thus, someone who has a detailed grasp of one phenomenon in biology is seen as more likely to have a deep grasp of another biological phenomenon than a person who has a deep grasp of one phenomenon in mechanics. This inference holds even if the two phenomena in biology are quite different, such as plant growth and human disease (Erickson, Keil, & Lockhart, 2010). By kindergarten, children can cluster experts in such large domains as physical mechanics, living kinds, social interactions, economics, and the like, and they do so by considering very broad and abstract causal patterns that are common to such domains (Keil et al., 2008). There are major developmental changes as well concerning the ability to avoid distraction by other forms of expertise (Danovitch & Keil, 2004; Keil et al., 2008), but at all ages children are able to use their sense of high-level causal patterns to make at least modest inferences about the division of cognitive labor in the culture around them.

In short, one way to address the apparent poverty of detailed mechanistic understandings is to recognize that a person who is clearly unable to provide virtually any details about the workings of biological systems, natural phenomena, or everyday devices, can be quite sophisticated in the ability to sense how broader causal patterns are linked to large domains such as intentional agents, living kinds, and tools. Moreover, such individuals can use their knowledge of these broader causal patterns to discern relevant sources of expertise. The presence of these forms of causal understanding in preschoolers, and even to some extent in infants, raises questions about what develops. To what extent do older children and adults go beyond these very early ways of tracking high-level causal patterns and area regularities? The full answer is not yet clear, but there are at least some dramatic patterns of change that suggest what develops and why.

Changing Patterns of Causal Understanding

Although children certainly show some increases in their causal understandings at the level of mechanism, I have suggested that progress in this area should not be the sole benchmark of emerging causal understanding. What, then, develops at levels other than clockworks understandings? One developmental change may involve more subtle refinements in understanding causal patterns at an intermediate level of generalization. Consider, for example, changes in thought about essences. A large body of evidence now supports the idea that children, toddlers, and perhaps even infants have essentialist biases in terms of how they interpret the behaviors and properties of other entities (e.g., Gelman, 2003; Newman & Keil, 2008). Children of all ages seem to assume that, for natural kinds at least, there are microstructural essences that are causally responsible for most phenomenal properties and behaviors of entities such as living kinds. This, then, is a form of highly abstract causal understanding.

Beneath that level of essentialist understanding, however, lie questions about how such a causal relationship is to be instantiated. For example, is the essence that results in surface properties evenly distributed throughout the substance of a natural kind, or does it have a central focus out of which causal arrows project to create surface features? It may seem obvious to adults that essences are homogeneously distributed, but this relation is not at all obvious to children, even those who are in the early years of elementary school. Thus, when children are asked to choose between causal patterns that have essential features evenly distributed throughout an organism versus patterns that have essences concentrated in just one location, younger children tend to choose focal locations in which the essence is localized in just one small region within the natural kind such that only that region is seen as causing surface properties. There is then a marked developmental shift to more distributed views that occurs in the later elementary school years (Newman & Keil, 2008). For artifacts, there is no shift, because children and adults alike tend to think that essences are localized to a particular part of the internal architecture. Thus, a particular local piece of machinery is thought to be the causal essence that distinguishes otherwise very similar artifacts, such as microwaves versus toaster ovens. For adults, of course, this is not true for similar natural kinds.

This developmental shift is not to a highly specific account of internal structure. Thus, fourth graders who strongly prefer the homogeneous view of essences still have almost no concrete idea of what the essences are. Almost no fourth graders referred to DNA or some other version of a genetic code (Newman & Keil, 2008). Their notion of a distributed essence was still largely unspecified in terms of its constituents. Nonetheless, they strongly felt that the essence could be found throughout the insides of an animal or plant. This understanding, then, represents a major developmental shift, and one that is in the direction of a more accurate account of real causal relations. Of course, the actual causal story of how microstructural biological insides cause surface properties is vastly more complicated and requires a grasp of the ontogenetic unfolding of biological structures and properties from a single fertilized egg, none of which most children or adults know. Thus, there is developmental change here, but all of it occurs at a level far above that of knowledge of specific biological components and their workings. It may well be that some of the more dramatic developmental changes in causal understanding occur at this intermediate level, below that of the highest causal gloss of a system but still far above the level of concrete, specific mechanisms.

The initial bias toward more focal causes may be related to a broader bias in terms of how children and adults alike interpret causal pathways. In particular, in several categorization tasks, people tended to favor the causes in a causal chain as opposed to the effects, even when both were equally well correlated with a set of entities; they also tended to favor the first causal element in a chain. This bias, known as the *causal status effect* (Ahn & Kim, 2000), has been demonstrated at many ages (Ahn, Gelman, Amsterlaw, Hohnstein, & Kalish, 2000; Meunier & Cordier, 2009). It may be that, all other things being equal, this bias causes a tendency to favor accounts in which there are focal single causes. It is not clear how children come to overrule this early bias, because they do not acquire a specific DNA mediated mechanism; but they do seem to first get the insight for nonliving natural kinds and then extend it to living kinds (Newman & Keil, 2008).

What might be some other ways in which causal understanding develops at this intermediate level between very broad causal biases, such as essentialism and specific concrete mechanisms? Some are likely to revolve around learning to apprehend such causal phenomena as negative and positive feedback loops, interactions instead of simple main effects, homeostasis, and symbiosis. In each case, children proceed from a position of ignorance or misconception to a closer approximation of the real causal pattern while nonetheless knowing almost nothing about the actual biological or physical instantiation of the process. These levels of causal understanding of the real world lie largely uncharted in developmental research, and yet they may be where some of the most dramatic changes occur.

Learning to Use Causal Information to Guide Discovery and Exploration

In addition to learning more about midlevel causal patterns that provide some information about the functioning of entities, children also learn about other sorts of causal information that they can use to guide information-seeking behavior.

This knowledge is less about how things function at any level and more about general causal characteristics. For example, adults have strong intuitions of the domains that are governed by rich causal relations as opposed to those that have almost no intrinsic causal patterns. We all know that “dogs that hunt” is a much more causally rich category than “dogs with red collars.” This knowledge in turn enables us to infer that there are likely to be expert resources on dogs that hunt but not on dogs with red collars, or that if we want to learn more about either topic there will be much more to learn about the category of dogs that hunt. It also tells us when we are likely to know all there is to know about a category as opposed to being novices in need of help. In short, some categories are merely categories because of one criterion that is common to all members. Others have members that cluster because of a rich network of causal relations, such as those behavioral, biological, and physical attributes that interact to make some kinds of dogs successful hunting dogs.

Despite the seemingly obvious contrast between these two kinds of categories, young children do not seem to grasp that one is much more causally dense than another. When kindergarteners are asked to judge which person would know more—one who knows all about dogs with red collars or one who knows all about dogs that hunt—they perform at chance levels. In contrast, fourth graders have the strong conviction that the person who knows all about dogs that hunt knows a great deal more (Keil, 2010). Across a wide variety of cases, young children have great difficulty distinguishing between categories that have a rich causal density and those that are causally empty and defined merely by a single criterion. By fourth grade, they are quite sophisticated.

However it seems that fourth graders have not developed a rich understanding of the functioning of members of these causally rich categories but rather have acquired the coarser sense that there is a complex web of causal relations underlying some categories and not others. Indeed, many of the fourth graders who strongly preferred some categories over others were often unable to provide any details at all about the nature of those causally dense relations (Keil, 2010). How, then, could such an understanding be of any use? One important benefit concerns heuristics that tell a child when a domain is worthy of future study or one for which they should keep track of experts whom they might want to access at a later date. Similarly, a sense of causal density might guide children’s evaluations of the plausibility of alleged experts. Experts have knowledge about causal substance as opposed to more trivial knowledge. When we expand folk science by learning to use knowledge that exists in other minds, the ability to track causal density might be valuable even if it offers little direct insight into the nature of a category on its own. Kindergartners do not seem to be very able to use causal density to such an end, whereas fourth graders can do so with great potential effectiveness. It may be that future tasks will uncover some degree of this skill in younger children, but the studies conducted so far suggest that in those early ages it is likely to be fragile and not nearly as useful a guide to fruitful domains of information.

Many other kinds of causal information might be used in a similar manner to guide searches for more information, to know when to defer, and to evaluate alleged experts and alleged areas of expertise. For example, one can know whether information in an explanation seems to cohere as opposed to being a grab bag of largely unrelated statements. Thus, one should be more satisfied with explanations that show coherence, and seek information that increases coherence where possible. There are several ways to assess coherence that again can work at levels far above those of mechanism. For example, one can assess the likelihood that individual statements will be true given that others are true on the basis of a sense of conjoint probabilities of various event types (A. J. L. Harris & Hahn, 2009). Coherence can also be crudely assessed by the simple extent to which a set of statements tend to refer to each other without direct contradictions.

One can also know whether an explanation provides a concise gist as opposed to expanding on true but excessive detail for the task at hand. This sense can go above the level of mechanism in several ways. For example, there are structural clues to which ideas elaborate on others. Text passages that contain more ideas on which others elaborate are seen as creating better gists than those that contain more ideas that are themselves elaborations. Gists can be constructed in this way by automated systems that have no real grasp of conceptual content (Marcu, 2000), and it appears that similar heuristics are easily used by laypeople (Rottman & Keil, in press).

Another way to evaluate explanations involves knowing that lines of evidence in an explanation provide a stronger argument when they converge from several different angles as opposed to repeatedly coming from the same subdomain (a very old idea in the philosophy of science known as *consilience;* William Whewell, 1847). One can sense this pattern of convergence without grasping much detail (Kim & Keil, 2003; Kim, Yopchick, & de Kwaadsteniet, 2008), and it seems likely that children may acquire sensitivity to such information during middle childhood. For example, in related tasks that examined the use of sample diversity in inductive reasoning, there is marked improvement in the use of diversity during the elementary and middle school years (Heit & Hahn, 2001; Rhodes, Brickman, & Gelman, 2008).

Several current research projects exploring these and other facets of causal information that might guide searches for the best explanation. On the basis of preliminary findings, there seem to be marked developmental improvements in children’s abilities to use all this information during the elementary school years. Some of the most important developmental changes may occur at this level of tracking causal patterns and using such patterns to seek and assess explanations.

Evaluating Explanations on Noncausal Grounds

I have argued that there are many levels of causal information in the world and that a tendency to focus on a level corresponding to clockworks mechanisms grossly underestimates the ways that both adults and children can use causal information to further their understanding. I have further argued that young children, well before the start of formal schooling, have a head start on this process by showing impressive sensitivities to causal patterns at these higher levels. At the same time, there are marked developmental changes during the elementary school years as children start to sense more finely grained causal patterns and then use those patterns in ways that involve seeking and evaluating knowledge, and knowing when they are and are not likely to need to defer to others. This account might seem to be the full story of folk science development, but there are several other aspects to what we would call folk science in all cultures that do not directly involve the apprehension of causal information at any level.

One facet concerns *circularity* in explanations. Although even adults can embrace circular arguments when the circles are large enough, a very small and explicit circle is easy for adults to discount. If one encounters an explanation of how brakes work that states that they work by reducing the speed of a device, one immediately realizes that no real explanation has been provided. The ability to see such circularities covers both causal circularities (e.g., the one just mentioned) as well as noncausal ones. For example, an explanation that a triangle has lines creating three vertices might be considered circular because it merely restates that it is a figure with three angles. It appears that the ability to see circularity in both causal and noncausal domains is a gradually emerging ability that may be crudely present in preschoolers in the right sorts of supporting contexts, but it becomes much more powerful during the elementary school years (Baum, Danovitch, & Keil, 2008; Sperber & Mercier, in press). In its most general terms, this ability seems to involve a sense of the actual circle of propositions regardless of the details of their content, because circularity can be stated over essentially blank propositions represented only by unelaborated and largely unfamiliar words (Brem 2003; Rips, 2002).

A different class of factors concerns a burgeoning literature on information about an informant's *competence* (P. L. Harris, 2007). Children use several forms of information to either discount or embrace what an informant tells them. If an informant has made factual mistakes in the past, even preschoolers are likely to discount any information that is provided after that point (Jaswal & Neely, 2006; Koenig & Harris, 2005; Vanderborght & Jaswal, 2009). If an informant is accepted by others whom the child trusts, the child is more likely to trust the informant—a kind of transitivity of the trust relationship. If an informant indicates hesitation, lack of confidence, or simply seems to be stupid, all those factors can cause the informant's testimony to be discounted. It is now clear that even preschoolers have intuitions along these lines (see preceding discussion), even as the skills become more robust during the school years.

A different dimension of trust in testimony concerns inferences about the motivations underlying another's testimony. When someone declares something that is blatantly self-serving, adults are usually quite likely to be skeptical about its truth. The candidate who declares that he is certainly the most qualified for a job is much less likely to be believed than the candidate who declares that another is the most qualified for a job (even if that is not a winning strategy). By the second grade, children clearly take into account such inferred motivations. It is interesting that younger children may not able to use this skill, and will sometimes actually think that statements supporting self-interest are more true (Mills & Keil, 2005, 2008), again indicating an important area of development in a broader characterization of folk science.

It might seem that the literature on children's trust is not the same as their having folk scientific knowledge, but a little reflection on the nature of formal science reveals that it would be odd if it were not also part of folk science. The formal sciences depend profoundly on trust and deference (Hardwig, 1991).

Even the supposed polymaths of earlier times, who are often envisioned as laboring as lone wolves, are well known for acknowledging how much of their formal science depended on others. Indeed, Newton felt a large debt to those scientists who preceded him. Although Newton is famous for laboring endless hours alone in an effort to understand many areas of physics and mathematics (Gleick, 2003), his interactions with others had profound influences on the growth of his ideas. In a 1676 letter to Robert Hooke, Newton explicitly acknowledged his debts when he wrote, “If I have seen further it is only by standing on the shoulders of giants” (quoted in Turnbull, 1959, p. 297). Elsewhere, Newton acknowledged the clear need for a division of cognitive labor, and in doing so cast doubt on the idea of true polymaths even in his time:

> To explain all nature is too difficult a task for any one man or even for any one age. ‘Tis much better to do a little with certainty, & leave the rest for others that come after you, than to explain all things by conjecture without making sure of anything. (quoted in Westfall, 1980, p. 643)

Newton here seems to be capturing something quite basic about formal science: It is possible to have detailed highly specific knowledge in narrow slivers of expertise, but even in the early 1700s one could not hope to have comprehensive understandings across many domains. Formal scientists had to rely on slivers of expertise in other minds to support their own.

Perhaps folk sciences should be understood in different terms, as instances of the actions of solitary agents making sense of the world on their own. This conjecture, however, does not ring true. A little reflection reveals that the body of information that even a young child acquires through indirect means is enormous. For many preschoolers, most of the animals that they can recognize may have been learned through books or stories. The animal vocabularies of many North American children may be dominated by words for large African mammals, even when many of those children have never seen any of those animals directly, even in zoos. Witches, ghosts, and dinosaurs are all common concepts in preschoolers, even though we can be quite sure they have never encountered them firsthand.

It also does not seem to be the case that preschoolers are completely gullible sponges, indiscriminately absorbing any information that comes their way. To be sure, they can be fooled in ways that older children cannot, but they also seem to have some sense of the plausibility of explanations and can reject a wildly implausible explanation as well as an older child or an adult can (Shtulman & Carey, 2007). They see some claims as much sillier than others and will say so with confidence. Despite claims that children are ideal propagators of memes because of their complete gullibility (Dawkins, 1993), they are in fact quite able to doubt what some adults say, and they do so on reasonable grounds. In this way, they are able to titrate the value of information that they learn through others.

Thus, a large proportion of the information that children acquire about the world is learned not firsthand but through other sources, and from early on in the preschool years they understand that sources vary in quality. The ability to evaluate such sources is therefore not just a late-developing skill arising from formal instruction but instead a foundational part of the intrinsically social nature of knowledge acquisition. Whether it be learning a new word, how a device works, or about an invisible entity, children as young as preschool will focus more on information that conforms with positive evaluations of others.

This sense of the importance of sources of information may build on related abilities that appear in infancy. Consider, for example, differences in the extent to which infants rely on social referencing as a function of how much they trust and are familiar with adults who are indicating an emotional reaction to a situation or a stimulus (Corriveau, Meints, & Harris, 2009). They will titrate the perceived usefulness of another's emotional attitudes as a function of past experience with that person. They will also tend to trust others more when their attachment style to them is more secure.

Influences of Folk Science on Formal Science

In most cultures of the world today, folk science is no longer the only game in town. Young children in many cultures have heard of scientists, or other kinds of experts in science, technology, engineering, and math, even if they often hold narrow stereotypes of those experts (Newton & Newton, 1998). The question then arises as to how these emerging senses of formal science, and scientists, are linked to folk science. Do notions of formal science primarily trickle down to influence folk science, do ideas in folk science primarily invade formal sciences largely as misconceptions and misconstruals, or is there a more complex commerce in both directions? My sense is that the influence clearly runs in both directions and that the nature of these influences may be a major area of developmental change during the school years. In addition, we now may want to see the folk sciences as not simply clouding the formal sciences but as often providing cognitive tools that make the formal sciences more tractable and reliable.

Consider some ways in which folk science expertise might make a child's understanding of the formal sciences become more nuanced. Take, for example, the ability of elementary school children to consider an informant's self-interests in evaluating the message (Mills & Keil, 2005). Surprisingly, such factors are not always taken into account in the formal sciences. Indeed, it is only a relatively recent practice for newspaper reports of formal science research to describe the funding for that research and whether the research findings might benefit the funding agents. Even then, such practices tend to be regularly used at only the most prestigious national newspapers. Similarly, only recently have some scientific journals and universities started to ask for such information from formal scientists. Other subtle cues that children use to evaluate the credibility of sources may be similarly incorporated into the formal sciences, although such effects are not yet documented by experimental research.

Formal scientists may also benefit from children's skills at using coarse gists of causal relations to infer domains of knowledge and patterns of deference. Ask formal scientists how they know which experts to consult when buttressing their own activities, and they will almost always say that knowledge is intuitive and built from hunches and implicit heuristics. Given that even preschoolers use such heuristics to infer how knowledge clusters in other minds and how understanding of one phenomenon suggests understandings of other causally similar phenomena, it seems reasonable that the same heuristics are at work in formal scientists. For example, a cell biologist who is unsure about the physical constraints governing the sensitivity of electron microscopes has hunches about which colleagues to consult that are quite different from when that same biologist is unsure about the thermodynamics of a particular chemical reaction. Although that scientist may have only the most minimal knowledge of each of those other areas, she may have enough of a rough sense of the underlying causal terrains to know whom to consult.

In a similar way, formal science is deeply dependent on creating idealizations so that systems can be studied in a tractable manner, a skill that is widely used but that may arise from much more intuitive processes that begin in childhood. Scientists also make simplifying assumptions so as to prune a causal briar patch into something more elegant and cognitively manageable. They seem to do so in several ways. First, they tend to stick to one level of a reductionist hierarchy, not diving deeper to lower levels (Owens, 1989; Wilson & Keil, 1998). For example, some psychologists may try to envision how cognitive structures and processes are constrained by the biology of the nervous system, but they rarely if ever try to fully specify a mechanistic model of what is happening at the cellular level. Similarly, while attending to chemistry, the biologist also stops short of details that occupy chemists. Thus, few biologists ask how quantum bond angles are relevant to an aspect of cellular metabolism. Because we don’t have a reliable way of specifying levels of reduction and whether there really are clearly objective levels that apply in the same way across all the subspecialties of such major areas as psychology, biology, chemistry, and physics, it is difficult to understand how scientists refrain from crossing levels. Somehow, scientists in practice draw these lines all the time to make their task more manageable, and they do so in a way that allows their science to advance.

A second kind of simplifying assumption is to make one’s science “local” by ruling out those tendrils of causal influence that, although technically present, can be ignored for the purposes of the scientific task at hand. Without such simplifications, one runs the risk of having to consider the ways in which almost any event can potentially have a causal influence on any other that follows later—a scientific version of the “butterfly effect” problem (Hilborn, 2004). Elga (2007) considered this problem in detail and suggested that both scientists and laypeople see the world as localized nets of causal relations. Those nets form clumps and clusters that can be considered as stand-alone systems in which more remote influences are disregarded. When trying to understand the behavior of billiard balls on a table, we tend to consider just the forces at play between objects on the table, even though there are very small but real influences exerted by the moon; the people in the room; and countless other objects and events, such as sound waves. We may technically eliminate effects that would have to travel faster than the speed of light to have an influence (things outside what physicists call the *light cone;* Elga, 2007), but there is still a vast array of other real influences that are simply below some threshold in almost all matters of scientific inquiry.

Finally, scientists construct ideal systems that depart from reality in clearly fictitious but necessary ways to do the science. For a given task, physicists may ignore friction or air resistance. In another, biologists may disregard mutation rates on a genome. In still another, psychologists may not consider the time of day or time in a semester when conducting a study on reasoning. However, all these idealizations are exquisitely context sensitive and are adjusted on the fly in ways that are usually implicit but that can be central to the success of an experiment. For certain problems in mechanics, friction or air resistance is everything. Some questions in biology, including a number of formal computational models, rely critically on mutation rates. Finally, we all know how time of day or semester can wreak havoc with some kinds of cognitive tasks (Anderson & Revelle, 1994). Scientists effortlessly slip into idealizations, sometimes carefully specifying the idealized dimensions, at other times doing so in a largely implicit manner, but always in ways that can significantly depart from reality by making what can be enormous simplifications.

One analysis suggests three distinct kinds of idealizations: (a) those driven by a need for simplicity to make a problem tractable even if it distorts relations; (b) those in which only factors that make a causal difference for giving rise to the phenomenon are considered; and (c) those that acknowledge multiple idealizations for the same set of phenomena, all of which might be true but that can also be incompatible with each other (M. Weisberg, 2011). All three forms involve intricate cognitive decisions about how to construct a particular idealization. Moreover, although there are attempts to formalize some ways of constructing such idealizations (M. Weisberg, 2011), much of the process appears to occur at a more implicit level, a level that might also be at work in everyday folk science. Even in the heights of analytical science, the process through which scientists focus on certain causal processes and relations as most relevant is described as more of an art than an analytically driven procedure (Strevens, 2009).

It seems quite plausible that all of the processes that formal scientists use to simplify problems to make them cognitively tractable have their roots in the earliest forms of folk science in young children. Thus, with even more limited cognitive capacities, children must necessarily make gross simplifications in their attempts to understand complex systems. Scientists do not yet know what heuristics they use, but they might well show patterns that are later incorporated into the more formal sciences, such as tending to stay at one level of analysis, ignoring remote influences, and thinking in terms of idealizations even when they do not explicitly characterize them as such. One could even characterize some of their early attempts to induce oversimplified rules for systems as forms of idealizations (Klahr, 2000).

Influences of Formal Science on Folk Science

In the other direction, information in the formal sciences can trickle down to influence the folk sciences in several distinct ways. First, the formal sciences may provide more precise sources on which to ground deference. They can do this by providing labels or institutions as brands of expertise. They can also create stereotypes of scientists that, although misleading in many ways (Newton & Newton, 1998), may have some crude utility as indicators of more reliable sources of information. Similarly, stereotypes of laboratories, experiments, and research institutions may serve as rough guides to areas of expertise. The mere idea of such groups of specialized experts may prompt a search for cues to areas of expertise when one is in doubt.

The formal sciences may also introduce ideas that, although barely understood, can become seeds around which a new area of folk understanding can crystallize. Consider, for example, the concept of a *gene.* Most Western adults are very familiar with the term and may think they understand its meaning in some detail, even if they know little beyond the idea that something inside each of our body's cells has information that is responsible for traits. This idea, however, can quickly become a way of instantiating essentialism and of offering pat explanations for complex behaviors (the "gene for *x*" syndrome that is so prevalent in the press). This trickle-down effect may often cause serious distortions in laypeople's understanding, as well as in some scientists. Thus, the expected yields of the Human Genome Project (http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml) were vastly higher than the actual yields to date (Goldstein, 2009). Laypeople and some scientists seemed to assume that there would be straightforward accounts of genetic influences on disease, such that certain alleles would be uncovered for various widespread diseases. Instead, there seems to be an extraordinary array of very rare variants that create disease, often in complex combinations, such that for the vast majority of common diseases, as well as for highly heritable traits (e.g., physical height), scientists have little idea of the genetic causes. "Genes" may have been a convenient conceptual hook on which to hang ideas about simple classes of general causes, but the ways that laypeople interpret them may also have resulted in several distortions, some of which may have originally come from formal scientists in their attempts to explain the benefits of the Human Genome Project.

Another downward influence of formal science on folk science is to describe a new technology around which new folk ideas can be organized. In some cases, however, the new technology is unwittingly interpreted in metaphorical terms that can cause serious distortions as well. Consider, for example, how the layperson typically understands neuroimaging data such as those generated by functional magnetic resonance imaging (fMRI). Partly because of some distortions introduced by the ways that scientists present information, the layperson often assumes that fMRI images of the brain with various areas "glowing" are analogous to a brain X-ray, when in fact such representations are only superficially similar and in reality reflect massive amounts of data processing and inference. People are unaware of the large inferential distance that separates initial signals received in an fMRI scanner and the final graphical representations. When they seize on the fMRI representations as photograph-like X-rays of the brain, they introduce other distortions of understanding (Roskies, 2008). In addition, they tend to weigh the information provided by neuroimaging data far more strongly than its real informational value would justify (McCabe & Castel, 2008; D. S. Weisberg, Keil, Goodstein, Rawson, & Gray, 2008).

These trickle-down effects describe ways in which formal science ideas can become distorted in folk science, even as they can also provide some new ways of understanding phenomena. There are, of course, many other influences of the folk sciences concerning ways to engage in inquiry and discovery. Older children do gradually learn subtle aspects of science as practice, such as causes of error, the need for decent sample sizes, and the importance of various controls. One poorly understood question concerns the extent to which the properties of the sciences as practices filter down to laypeople in ways that go beyond explicit instruction in the classroom. Does one learn to appreciate some of the methodological principles of the sciences by simply growing up in a culture and observing references to scientific studies in the media? There seems to be little evidence of such influences to date.

In short, there are many influences between the formal sciences and folk sciences that are not simple additions of formal knowledge onto the informal, or simple warnings about the fallibility of formal scientists arising from intuitions about the fallibility of folk scientists. Instead, the reciprocal effects are much more complex, both within the individual and within the mutual interactions in learning environment. Researchers are just beginning to understand how such influences among folk and formal sciences might work.

Conclusions and Future Directions

From one point of view, in which the folk sciences are described as mechanistic models of how the world works, the question of what develops seems quite mysterious because the end state is so minimal. Adults have almost no detailed understandings of how most everyday devices work, how living kinds function, or why natural phenomena occur as they do. This ignorance is often masked by illusions of explanatory competence that are easy to document in adults. If this is all there is to folk science, then development simply consists of just a few largely insignificant additions to the very coarse causal understandings we find in young children. From a different point of view that embraces a much broader notion of folk scientific competence, however, the developmental story is much more interesting.

This broader view includes an emerging understanding of discovery and induction processes, an area where the work of David Klahr has been so pioneering and pivotal. It also includes different ways of characterizing how individuals track causal structure and relations. There is a rich array of causal patterns at levels far above those of concrete mechanisms, and it is at these levels that young children are surprisingly adept in sensing patterns for such factors as causes of order, ways to ascribe function, and domains with rich versus shallow causal underpinnings. Children track all this information while being largely ignorant about mechanistic details. Development often seems to consist of moving down a bit in the levels at which information is tracked but still staying at levels above the mechanistic. Thus, elementary school children may shift in how they think essences are instantiated, but even the more mature form of such an understanding has none of the details of such elements as DNA. Children are then able to use all the ways they track causal patterns to evaluate both the quality of explanations and the credibility of alleged experts. They are also able to make inferences about likely areas of expertise and how to navigate the divisions of cognitive labor that are so intrinsic to all cultures. In all these respects, although even preschoolers show some evidence of these skills, there are dramatic increases in their effectiveness over the elementary and middle school years.

Folk science also develops in ways that do not involve causal information, such as techniques for evaluating the structures of explanations (e.g., circularity) and the ways in which the motives of informants and experts need to be considered in evaluating any information or explanations that they might provide. Here, too, there are major changes during the school years. The social infrastructure that supports and constrains scientific thought is complex and is an area where there is a great deal of growth during middle childhood.

All of these facets of folk science that go beyond simple mechanistic understanding also have an influence on the formal sciences. Many of the formal science practices, such as constructing gists, deferring to others, and making idealizations, are not taught and are not associated with explicit procedures. It seems very likely that formal scientists use those untaught intuitive skills that developed during early and middle childhood and that an understanding of how those aspects of folk science develop will greatly inform formal science as well. Finally, because of these subtle patterns, the ways that formal sciences influence the folk sciences are much more intricate and full of cycles of interactions than they are the simple replacing of misconceptions with correct ones or the grafting of details onto gaps in folk science.

The most provocative implication here is that we may learn a good deal more about how the formal sciences function by looking at all the ways that the folk sciences develop most dramatically, ways that involve causal patterns far above those of mechanism and that rely heavily on the social infrastructures in which folk sciences are embedded.

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