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The Magic of Mechanism: Explanation-Based Instruction on Counterintuitive Concepts in Early Childhood

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Abstract
Common-sense intuitions can be useful guides in everyday life and problem solving. However, they can also impede formal science learning and provide the basis for robust scientific misconceptions. Addressing such misconceptions has generally been viewed as the province of secondary schooling. However, in this article, I argue that for a set of foundational but highly counterintuitive ideas (e.g., evolution by natural selection), coherent causal-explanatory instruction—instruction that emphasizes the multifaceted mechanisms underpinning natural phenomena—should be initiated much sooner, in early elementary school. This proposal is motivated by various findings from research in the cognitive, developmental, and learning sciences. For example, it has been shown that explanatory biases that render students susceptible to intuitively based scientific misconceptions emerge early in development. Furthermore, findings also reveal that once developed, such misconceptions are not revised and replaced by subsequently learned scientific theories but competitively coexist alongside them. Taken together, this research, along with studies revealing the viability of early coherent explanation-based instruction on counterintuitive theories, have significant implications for the timing, structure, and scope of early science education.

Keywords
counterintuitive, explanation, mechanism, science learning, children, evolution

"Intuition takes me everywhere," wrote John Lennon (1973). But science educators might beg to disagree. Intuitive explanatory frameworks emerge as individuals integrate information gleaned from firsthand experiences (e.g., direct observations) and secondhand sources (e.g., conversations) with their causal preconceptions and existing knowledge. Although elements of these frameworks can act as conceptual resources during the acquisition of scientific knowledge, it has long been acknowledged that these intuitive explanations can also create enduring obstacles to formal science learning and reasoning. This is because they often involve categories and causal assumptions that are profoundly at odds with those of canonical scientific theories (e.g., Carey, 1991; Chi, 2009). Thus, they can provide the basis for enduring misconceptions about core scientific mechanisms and lead to false scientific beliefs, for example, that bacteria mutate to become drug-resistant, that heating a substance essentially destroys it, and that whales and hippos bear no biological relationship to each other (e.g., Coley & Tanner, 2012, 2015; Leonard, Kalinowski, & Andrews, 2014; Vosniadou, 2012).

The task of addressing such intuitively based misconceptions has generally been viewed as the province of secondary schools, where coherent science instruction typically begins in earnest in most countries. However, in this article, I suggest that leaving matters until adolescence is too late when considering a subset of scientific concepts that are pivotal but deeply counterintuitive (e.g., evolution by natural selection) and when thinking about them in relation to a series of cognitive developmental factors (such as children's early-emerging explanatory tendencies). Instead, we should begin focusing on explanatory frameworks much earlier, in early elementary school. Furthermore, it is not only the timing of such early content instruction that needs to

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be reconsidered but also its structure. The reason for this is twofold.

First, despite policy-reform recommendations, contemporary early-elementary science-education practice tends to be broad rather than deep (e.g., Duschl, Schweingruber, & Shouse, 2007; Oates, 2011). In addition to covering an abundance of topics, the approach tends to emphasize piecemeal facts, descriptions, or isolated cause-and-effect associations rather than comprehensive, coherent, causal-explanatory frameworks (Braaten & Windschitl, 2011), that is, explanatory frameworks that elucidate underlying mechanisms by causally integrating a corpus of domain-specific facts in internally consistent ways (Keil, 2006; Thagard, 1989). This lack of comprehensive causal explanation is unfortunate not only because causal accounts guide learning and motivate inquiry (e.g., Frazier, Gelman, & Wellman, 2016; Legare, 2012; Lombrozo, Bonawitz, & Scalise, 2018) but also because, in their absence, children will formulate explanations on their own (e.g., Carey, 1985; Gopnik & Wellman, 2012; Vosniadou, 2012). Of course, in itself, such a manifestation of curiosity is very far from an issue. Rather, the concern is how children's explanatory drives can interact with early piecemeal science instruction in specific cases involving foundational, unifying counterintuitive principles.

Because the intuitive explanations that children self-generate are often shaped by compelling phenomenal experiences or early-emerging cognitive biases—for example, the teleological tendency to favor purpose-based explanations (Kelemen, 2004)—they easily overpower the theoretically decontextualized fragments of counterintuitive scientific information learned in early science lessons. After all, it takes a theory to challenge a theory. As a result, the formally learned fragments are likely to be filtered out or blended in with children's intuitive preconceptions, cementing a foundation for intuitively based scientific misconceptions that have years to entrench before adolescents finally encounter more comprehensive science instruction in secondary school (e.g., Vosniadou, 2012). Overcoming this more ingrained intuitive foundation requires far more effort by this point, perhaps helping to account for the fact that children's motivation for science learning often wanes significantly in adolescence (Donovan & Haeusler, 2015; Potvin & Hasni, 2014).

The second reason for reconsidering the structure of early science instruction relates to research on conceptual change. Although traditional constructivist perspectives within the study of cognitive development assume that explanatory frameworks are successively revised and replaced as learning occurs (e.g., Carey, Zaitchik, & Bascandziev, 2015; Gopnik & Wellman, 2012; Piaget, 1929; Vosniadou, 2012), a body of findings demonstrates that this is an oversimplification (e.g., E. M. Evans, Legare, & Rosengren, 2011; Kelemen & Rosset, 2009; Shtulman, 2017). Instead, scientific misconceptions about counterintuitive mechanisms seem both relatively inevitable and persistent. These are points worth emphasizing because they have implications for early science education that, as a result of disconnects between cognitive developmental research and educational practice, are generally overlooked. That is, once intuition-based scientific misconceptions are established, they are not supplanted by subsequently learned theories but instead tend to coexist alongside them. In this way, intuitive misconceptions can operate much as the representations of a habitual first language do in relation to a syntactically distinct, later-learned second language. For example, much like first-language representations, they not only need to be inhibited during the process of "second-language" acquisition but can also later reassert themselves to produce predictable performance errors, even in those who demonstrate scientific fluency (e.g., Finn & Hudson Kam, 2008; Marian & Spivey, 2003).

The implications here for the timing and structure of science instruction should be clear: Just as we would not expect students to become accurate and fluent speakers of a second language on the basis of piecemeal and delayed instruction (e.g., DeKeyser, 2012), neither should we expect it in the context of acquiring counterintuitive scientific theories. If we want to help students to fluidly activate scientifically accurate representations when the reasoning context demands it, then compelling, coherent instruction should start earlier. To clarify, this is not because of any imputed language-like "critical period" of science learning. The mechanics assumed here derive from skill-acquisition work and are far more mundane (e.g., Anderson, 1981): Practice from an earlier point in development is more likely to build robust representations that are more easily mobilized in the face of response competition from more automatic, inevitable intuition-based responses. Thus, the idea here is not so much that "practice makes perfect" but that "practice makes painless." This is particularly so if it commences during a developmental period when there may be less risk of interference from intuition-based responses because they are themselves at that point less habitual or ingrained.

In what follows, I flesh out these two considerations more thoroughly to build the case for why an earlier initiation of more comprehensive, coherent causal-explanatory instruction on pivotal counterintuitive ideas (e.g., natural selection) is not only viable but beneficial. To be clear, in talking about causal-explanatory science instruction, I mean instruction focused on elucidating generalizable natural mechanisms—in other words, the systems of predictably interacting physical or biological elements that causally relate natural phenomena (e.g., Johnson & Ahn, 2017). In due course, I also attempt to underscore some points about what this argument is not. To preface, I am not proposing that we should teach any and all scientific mechanisms in early elementary school simply because we can; nor am I proposing that we should presume that we can (or should) conceptually replace intuition-based frameworks that are useful heuristics in everyday life. Finally, it is certainly not an argument that we should teach scientific content at the expense of scientific practices or favor dull, didactic direct instruction over more engaging inquiry approaches. Indeed, on this last point, there is no absolutely no reason why coherent explanatory elementary science instruction on counterintuitive mechanisms such as natural selection or atomic theory cannot be fun and constructivist, leveraging children's own explanatory motivations to produce deep, transferable learning. In the final section of this article, I overview preliminary work from my own lab showing that early teaching of basic natural selection using mechanistically accurate narrative picture storybooks can have all of these properties (e.g., Kelemen, Emmons, Seston Schillaci, & Ganea, 2014). Before turning to that research, however, I start with an overview of why early formal and informal science instruction often does not invoke underlying causal-explanatory mechanisms and principles and why a more comprehensive explanation-rich approach is justified.

Explanatory Drives in Children

Even in countries in which scientific topics such as evolution are less politically charged than in the United States, instruction that comprehensively lays out the causal logic of a core but consistently misunderstood counterintuitive mechanism such as natural selection tends to be postponed until later in schooling (e.g., Australian Curriculum, Assessment and Reporting Authority, 2017; U.K. Department for Education, 2014). A primary reason for this delay in teaching such counterintuitive mechanistic ideas may be found in deep-seated assumptions about domain-general limits on young children's abilities to think abstractly, theorize, and explain (Metz, 2008). Yet one of the central lessons to emerge from the past 5 decades of post-Piagetian cognitive developmental research is that, despite real maturational limits on memory, attention, inhibitory control, and other executive-function resources (Hambrick & Engle, 2002), young children are not only more cognitively competent than is often assumed but also more active as informal folk theorizers (e.g., Gelman & Legare, 2011; Gopnik & Wellman, 2012; Keil, 2006).

From early in development, children construct explanatory frameworks around abstract domain-specific causal principles and categories. These frameworks then support explanations, predictions, and inferences about a range of physical, biological, psychological, and social phenomena. The oft-cited "why" questions from 2- and 3-year-olds offer a particularly marked early indicator of these explanatory urges (Callanan & Oakes, 1992). Furthermore, from preschool onward, children become increasingly discerning about the insights that they can yield, preferring not only explanations to descriptive factual statements (e.g., Alvarez & Booth, 2015) but also simple, broad, and inference-generating explanations to unparsimonious, circular, illogical, or factually questionable ones (e.g., Bonawitz & Lombrozo, 2012; Corriveau & Kurkul, 2014; Doebel, Rowell, & Koenig, 2016; Samarapungavan, 1992). Finally, they show greater curiosity and learning from explanations that elaborate causal connections or involve generalizable mechanistic processes compared with those that are more basic, for example, invoking only immediate causal antecedents (e.g., Frazier et al., 2016; Kelemen et al., 2014; Weisman & Markman, 2017; see also Mills, Danovitch, Rowles, & Campbell, 2017).

Given children's interest in explanations, and the cognitive and epistemic value of modeling and engaging in explanatory behavior (Beyer & Davis, 2008; Braaten & Windschitl, 2011), it is therefore sobering to consider how little explanation children often receive. Naturalistic data suggest that relevant causal explanatory answers to children's "how" and "why" questions can be relatively infrequent, whether children are interacting with parents or teachers or whether they are doing so in putatively conducive contexts, for example, science museums or schools (e.g., Crowley, Callanan, Tenenbaum, & Allen, 2002; Tenenbaum & Callanan, 2008). Indeed, explanatory question asking in the classroom rapidly declines from second grade onward, as children learn that it is not always welcome (e.g., Ronfard, Zambrana, Hermansen, & Kelemen, 2018; Van der Meij, 1988).

A significant question, then, is why adults often do not offer explanations, and multiple factors seem to be in play. Most straightforwardly, adults are frequently under time constraints and not only often lack explanatory knowledge but also, because of the idiosyncratic nature of metacognition, are usually unaware that they lack it until called on to explain (Keil, 2006; Kruger & Dunning, 1999). There are also more complex interpersonal dynamics involved. Parents and teachers have lay theories about children's intellectual and emotional capacities, and, ironically, children's naive efforts to fill explanatory gaps for themselves can feed these ideas in ways that further undermine adult motivations to explain. For instance, while adults find children's self-generated teleological or purpose-based explanations endearing (e.g., mountains originated "to stop the world from floating away"; Kelemen & DiYanni, 2005), they also view them as symptoms of children's vulnerability and cognitive immaturity (Bjorklund, Blasi, & Periss, 2010). It is an interpretation that echoes classic Piagetian views of young children as concrete and fundamentally limited—a view that almost guarantees that children will not be provided with rich or abstract causal-mechanical alternatives to their own conjectures.

Such a nonexplanatory dynamic may be a nonissue when children's intuitive ideas largely align with the ontological and causal assumptions of normative scientific theories (barring some isolated and easily corrected beliefs, e.g., "actually, the moon is made of rock not ice"; Carey, 1991; Chi, 2009). However, it has more thoroughgoing ramifications when children's ideas derive from broader frameworks that rest on assumptions deeply at odds with scientific accounts. In the case of a mechanism such as natural selection, children's teleological and essentialist intuitions about the purposes and invariant categories of nature help to produce just such a profound framework mismatch (Barnes, Evans, Hazel, Brownell, & Nesse, 2017; Shtulman & Schulz, 2008). Thus, adults' inability or reticence to accurately provide explanations at home or in school settings has broader implications.

Frameworks Involving Intuitive Teleological and Essentialist Ideas

Teleological explanations account for objects and events by reference to goals and purposes. They are useful facets of everyday common-sense reasoning: It makes sense to explain that people shout to attract attention and that cars exist to be driven. As goal-directed actions or intentionally designed artifacts, such events and objects did in fact originate to fulfill those goals or functions. However, across cultures, children extend teleological explanations beyond intention-based domains in which the causal history of objects and events renders them unambiguously warranted; they also favor them when considering a broad array of living and nonliving natural phenomena. For example, early-elementary schoolchildren will endorse ideas such as "rivers exist to shelter fish or provide water," an over-applied or promiscuous teleological approach that seems to blur the lines between natural and intentionally designed objects, sometimes quite explicitly (Kampourakis, 2018; Kelemen, 2004, 2012; Piaget, 1929; Schachner, Zhu, Li, & Kelemen, 2017; but see also Keil, 2006).

Of course, no one need care about this generalized teleological bias if, as Piaget assumed, it reflected a transient feature of early childhood. Yet the evidence from high school and undergraduate students suggests that the bias persists and can adversely influence accurate learning about a variety of scientific topics from secondary school onward. For example, in the physical sciences, students often teleologically misrepresent a range of thermodynamic and bonding processes, reasoning that osmosis occurs to reestablish balance, that electrons transfer to create stability, and that atoms combine to satisfy the octet rule (e.g., Taber, 2000; Talanquer, 2006). In the life sciences, in which teleological misconceptions have been a particular focus of study, the impact is even more overt, affecting students' reasoning about genetics, ecology, and, most amply documented of all, evolution by natural selection (e.g., Coley & Tanner, 2012, 2015; Gregory, 2009).

A scientifically accurate construal of natural selection involves understanding that it is a passive, undirected mechanism that occurs because of heritable variability within biological populations. Some individuals are more likely to survive and reproduce in particular environmental conditions than others, and the cumulative effects of this differential survival and reproduction result in trait adaptation and the evolution of new species over time. More than 30 years of research has demonstrated, however, that this is not the understanding held by most students, even after repeated instruction.

Rather than viewing natural selection as an undirected process, students instead predictably misconstrue it in teleological terms as a goal-directed event—one that transforms species and traits in response to functional need (e.g., Gregory, 2009; Southerland, Abrams, Cummins, & Anzelmo, 2001). Thus, even as their references to the mechanism might invoke standard scientific terms (e.g., evolution, selection, fitness), students' reasoning tends to reflect an intuitive framework in which species change takes place suddenly in an active, purposeful way, operating at the level of the individual rather than the population. A famous example is the ubiquitous belief that giraffes evolved long necks to reach leaves on tall trees. It is a misconception that, although sketchy on the mechanistic details, seems to locate the actions of the giraffes themselves or an anthropomorphized version of "evolution" as agents of goal-directed change (e.g., Gregory, 2009; Kelemen, 2012). Such transformationist misconceptions have a visceral common-sense logic, and their appeal is further undergirded by students' predilections for *essentialist reasoning*—a cognitive bias that intersects with the teleological bias and is also readily observable from early childhood.

Essentialism disposes individuals to believe that category labels pick out real naturally occurring categories whose members share a core, inviolable "essence"—an underlying internal characteristic that causes them to have a largely invariant identity, appearance, and behavior (Gelman, 2003). It is a bias that drives a tendency to view categories as eternally discrete, focusing attention on within-category similarities so that individual variability gets ignored. This obscures the reality that arises from this variability: Specifically the boundaries between distinctly labeled natural categories can be blurry and are also far from fixed (e.g., Gelman & Rhodes, 2012; Rhodes, 2012).

To be sure, essentialism has benefits for everyday common-sense reasoning. From early development it helps children go beyond the perceptual to recognize, for example, that gold remains gold even if it is painted silver and to infer that a baby rabbit that is raised by monkeys will still grow long ears (e.g., Gelman, 2003; Keil, 1989). However, from the perspective of formal learning in the evolutionary sciences, the downsides are significant. From early on, essentialism biases individuals against a belief that different species could be related (e.g., E. M. Evans, 2001; Samarapungavan & Wiers, 1997) and, by rendering them insensitive to phenotypic variation, undermines their abilities to accurately understand—even on the within-species or microevolutionary scale of trait adaptation—the selection mechanism that ultimately makes such relatedness possible (Shtulman & Schulz, 2008). Thus, from early childhood, teleological and essentialist biases act and interact to dispose mistaken beliefs that adaptations and new species arise through individual function-driven transformations of invariant categories that are generally viewed as eternal, fixed, and unchangeable (Emmons & Kelemen, 2015). These misrepresentations mean that formal evolution-science instruction encounters substantial challenges once it commences in adolescence: A framework that miscategorizes evolution by natural selection as involving individual-based need-driven transformative events simply cannot easily represent or interpret a cumulative population-based mechanistic process. The units and causal processes of each analysis are incompatible (e.g., Chi, 2009). As a result, during active problem-solving students resort to cobbling together syncretic concepts and a blend of ideas that, even if cloaked in scientific terms, are biased toward the intuitive (Rosengren, Brem, Evans, & Sinatra, 2012).

Furthermore, even motivated individuals who successfully inhibit their intuitions and elaborate an accurate representation of natural selection do not fully supplant their earlier framework in the process assumed by traditional revise-and-replace theories of conceptual change. Instead, in a manner more associated with dual-processing theories of judgment and decision making, the first language of intuitive framework-based ideas remains accessible, operating as the "heuristic" that takes precedence when information processing is taxed or when an individual is too tired or demotivated to effortfully engage a more remote framework of formally learned representations (e.g., E. M. Evans & Lane, 2011; Kelemen, Rottman, & Seston, 2013; Shtulman, 2017; see also Gupta, Hammer, & Redish, 2010; Slotta & Chi, 2006). Acknowledging this persistent explanatory coexistence, and the early developmental roots of explanatory drives and biases, provides further motivation for the current proposal that science instruction on counterintuitive concepts not only should emphasize the building of coherent explanatory frameworks but also should be initiated sooner than is now typically the case. Before returning to the reasons for this proposal, let us first consider some of the evidence of conceptual coexistence, particularly as it relates to a counterintuitive mechanism such as natural selection.

Evidence of Conceptual Coexistence

Dual-processing theories generally posit the existence of two rival modes of judgment and decision making: an easily activated, automatic, heuristic mode and a more effortfully activated, analytic mode (e.g., J. Evans & Stanovich, 2013; Kahneman, 2011). Such theories are broadly consistent with evidence that individuals who demonstrate highly accurate scientific reasoning in some contexts still default to persistent misconceptions in others. Research on teleological reasoning offers one illustration that is particularly relevant to understanding errors that can beleaguer highly schooled adults' reasoning about a process such as natural selection. Specifically, although promiscuous teleological attributions of purpose to nature appear largely absent when college-educated adults are tested on simple child measures (but see Casler & Kelemen, 2008, on nonschooled adults), such adults often revert to an underlying promiscuous teleological framework when they are tested on tasks that place them under cognitive duress to tap their gut intuitions. For instance, judging information at a rapid speed increases individuals' reliance on automatic default responses. When American and Chinese college-educated adults are asked to judge the accuracy of various explanations that are presented rapidly, they are significantly more likely than their nontimed counterparts to endorse scientifically inaccurate teleological statements about living and nonliving natural phenomena, some of which are directly relevant to evolution (e.g., "the fittest animals survive so that species can grow stronger"; Kelemen & Rosset, 2009; Rottman et al., 2017).

To clarify, this default to a teleological explanation does not arise because these adults experience more generalized difficulties reading and reasoning at higher speeds. The same participants show high accuracy and no equivalent deficit when judging control explanations involving accurate and inaccurate physical-causal explanations. What this pattern therefore suggests is that there is a cross-culturally recurrent, developmentally inevitable bias that is observable from early childhood and that provides a basis for enduring scientific misconceptions. Of course, one response to these results is that it is not surprising to find college-educated adults making such errors. However highly educated they might be within the global context, such individuals might not have quite the depth of motivation or background knowledge (e.g., about scientific norms) to be highly vigilant about making a teleological error. Furthermore, as has previously been reviewed, many have not overcome quite explicit teleological misconceptions during the course of their secondary science education.

Given this, it is therefore important to note that this bias has been documented not only in college-educated adults but also adults with far higher levels of training and motivation for scientific accuracy, specifically professional physical scientists at institutions such as Yale, the Massachusetts Institute of Technology, and Harvard. Indeed, although expert scientists' susceptibility to making a teleological error is lower than that of college-educated adults who have less schooling overall, under speeded conditions, scientists are almost twice as likely as their nonspeeded counterparts to endorse scientifically unwarranted statements (e.g., "rain falls in order to allow plants to grow"; Kelemen et al., 2013). Furthermore, across the different populations tested, a consistent predictor of adults' teleological bias is their independently assessed tendency to believe that nature is intrinsically charged with agency (i.e., Gaia beliefs). This lends credence to the idea that, despite being displayed in relation to a diverse range of biological and nonbiological natural phenomena, teleological intuitions are not isolated fragmentary ideas (e.g., diSessa, 2008; Southerland et al., 2001) but reflections of a more coherent underlying, potentially agent-based, framework.

Once constructed, a bias for reasoning about nature in terms of purpose and function therefore seems to be an abiding aspect of human nature, one that underlies a range of scientific misconceptions and retains a persistent influence on scientific problem solving, even in those who attain scientific fluency. But how do findings of this bias or related challenges to understanding evolution such as the "design bias"—which, across cultures, disposes one to the belief that natural phenomena are made by someone (Järnefelt, Zhu, Canfield, Chen, & Kelemen, 2018)—bear on the current claim? How does it follow that adults should not only informally explain more to children but also introduce them to coherent mechanistic explanations of concepts such as natural selection from early elementary school? The answer, as noted earlier, is that practice makes painless. If children are supported in using elements of their prior knowledge to elaborate accurate, counterintuitive mechanistic frameworks from earlier in development, such frameworks will become sufficiently familiar and representationally strong over time such that they stand a greater chance of being readily activated in the face of inevitable intuition-based modes of construal.

Note that this proposal—and the logic that it shares with second-language learning—does not solely apply to the counterintuitive concept of natural selection, although it is the case study here. Response competition between formal scientific understandings and intuition-based misconceptions have now been documented across numerous scientific-knowledge domains using a variety of paradigms, including neuroimaging studies (Goldberg & Thompson-Schill, 2009; Petitto & Dunbar, 2009; Shtulman, 2017; Zaitchik & Solomon, 2009). In short, if the primary goal of formal scientific education is, ultimately, to cultivate students' abilities to accurately represent and productively generalize canonical scientific knowledge, then it makes sense to initiate coherent mechanistic teaching of foundational but easily misconceived principles earlier rather than later. Doing so would yield more opportunities for practice from developmental periods when intuition-based frameworks may be less causally integrated, easier to inhibit, and thus less likely to filter formal learning and online reasoning.

Of course, the call for early explanatorily coherent science-education intervention might be all well and good, but should it really replace current emphases on the secondary and postsecondary education periods as the times targeted for remedying scientific misconceptions? This question is especially relevant because some instructional methods, such as those that encourage undergraduates to metacognitively reflect on their own misconceptions, show signs of promoting accurate learning (e.g., Beardsley, Bloom, & Wise, 2012; Southerland & Nadelson, 2012). The short answer is no: Early instruction should not replace later schooling as a point of emphasis. Instead, it should be more continuous with it as part of a spiraling sequence of content instruction (Bruner, 1960) that places as much focus on scaffolding coherent counterintuitive explanatory frameworks in elementary school as in middle school, high school, and beyond. In theory, this kind of progressive approach—which involves the systematic revisitation and elaboration of a constrained set of pivotal scientific concepts across schooling—was a primary goal of science-education reforms such as the Next Generation

Science Standards in the United States (NGSS; Achieve, Inc., 2013). However, although those streamlined standards have manifold strengths and were motivated by principles entirely consistent with the idea of initiating coherent causal-mechanistic instruction early on (Duschl et al., 2007), the goal of integration from elementary school has yet to be fully realized: Instead, preserving the status quo, the learning progressions of the NGSS (e.g., natural selection) remain mostly elaborated from the middle school years onward. Causes of this shortcoming may be traced in part to substantive practical considerations (e.g., limited resources for science professional development for nonspecialist elementary teachers). However, it also likely that there are other sources, including holdover ideas about children's abstract-reasoning limitations as well as the lack of a specific body of evidence on elementary-school children's intuitive and scientific theory building. So what evidence is there that, in early elementary school, comprehensive mechanistic instruction on a complex counterintuitive idea, such as natural selection, is even viable and can produce accurate, generalizable understanding?

A Mechanistic Approach to Counterintuitive Science Instruction

Even under science-education reforms (e.g., Achieve, Inc., 2013; U.K. Department for Education, 2014), early-elementary instruction for a topic such as natural selection remains focused on exposing children to relevant facts, for example, that biological populations vary and that they have adaptations that fit their environment. It does not focus on a mechanism that not only comprehensively causally relates these facts but also, when considered on progressively larger timescales, explains, in a nonessentialist way, how highly disparate species evolve from a common ancestor. To explore whether young children can take the foundational steps in elaborating such a unifying causal process, in a recent series of exploratory studies, (Kelemen et al., 2014; Emmons, Smith & Kelemen, 2016; Emmons, Lees & Kelemen, 2018) we examined what happens when 5- to 8-year-olds are taught a coherent mechanistic account of within-species adaptation by natural selection. Promoting an understanding of basic natural selection was thus a significant end in itself but also the first move in exploring the viability of a proposed learning sequence that focuses on progressively larger-scale evolutionary-change concepts (e.g., speciation and common descent). In initiating this sequence, the causal process of within-species adaptation was presented during a brief intervention involving an optimal pedagogical tool for young children and the adults who teach them: an explanatory picture storybook that was read aloud in a joint attentional context.

The storybook itself was short but not significantly condensed (see Legare, Lane, & Evans, 2013; Shtulman, Neal, & Lindquist, 2016). Over the course of 12 double pages, it provided a paced explanation of how realistic, fictional anteater-like mammals, "pilosas," went from being a species with mostly wider trunks to one with mostly skinny trunks as a result of environmental change. Specifically, the pilosas' insect food moved into skinny underground tunnels as a result of dramatic climate warming. The rare members of the population with a thinner trunk then ended up with a survival and reproductive advantage that caused their heritable trait to predominate over time (Kelemen and the Child Cognition Lab, 2017, 2018).

Although brief, the intervention involved several carefully designed components. First, there was the structure of the book: The text and pictures mapped directly to each other and involved simple nonanthropomorphic illustrations that did no more than depict the text, leaving little room for distraction or misconstrual (see also Anggoro, Stein, & Jee, 2012). Second, the narrative avoided teleological or intentional language as well as any function-based trait descriptions (e.g., "thinner trunks help get food") because, despite such form-function statements being a common feature of early educational practice, they invite teleological construal and have been found to increase children's essentialist insensitivity to within-species trait variability (Emmons & Kelemen, 2015). Third, the pilosas' trunks were described using relative terms (e.g., thinner, wider), which emphasized population variation rather than an essentialist view of pilosas as falling into wide- or thin-trunk "kinds." Finally, the structure of the book was gradual and cumulative. Each page integrated a new fact about the causal relationship between food and health, health and energy, energy and fecundity, fecundity and inheritance. Thus, with each turn of the page, children could frame out the mechanistic explanatory logic of why adaptation took place. The illustrations clearly portrayed how there was a proportional increase of animals with thinner trunks in the population over multiple generations via the inherently variation-based (i.e., nonteleological and nonessentialist) selection process of differential survival and reproduction.

In addition to the book, the assessments were also designed to be a central mechanism of learning by leveraging findings demonstrating the benefits of self-explanation (e.g., Fonseca & Chi, 2011; Walker, Lombrozo, Legare, & Gopnik, 2014). For example, a talk-aloud test of book comprehension required the children to explain how the change to the pilosas occurred so that if they had understood the account (and the book was designed to maximize this possibility) they could cement their understanding. Generalization assessments then had deep structural alignments to this comprehension test. Consequently, although the scenarios involved dissimilar species and foraging habitats, children who had understood adaptation had support in abstracting and applying the logic of the book. Of course, the flip side was that if they had not understood the mechanism in the book, then it would be clear across several assessments because, in the experimental setup, their answers were never corrected.

Using these materials, initial studies in which children were read the adaptation story individually in the lab and in urban afterschool settings revealed that many 5- to 6-year-olds and almost all 7- to 8-year-olds understood the selectionist logic of the book (Kelemen et al., 2014). This was true even in samples that, at pretest, displayed very sparse knowledge of the component biological facts (Emmons, Smith, & Kelemen, 2016). Many 5- to 6-year-olds could also generalize the theory, although the performance of these younger children varied by study (e.g., Emmons, Lees, & Kelemen, 2018): In some samples, they more reliably transferred only the isolated causal facts—generalizable explanatory elements that nevertheless serve as fodder for the later organization of a more comprehensive explanatory framework (see diSessa, 2008, on p-prims). However, in contrast to these younger children, 7- and 8-year-olds consistently transferred the population-based logic of natural selection across all studies and samples, and this remained true up to 3 months later. Furthermore, in work that involved urban classroom groups who analogically compared two storybooks, 7- and 8-year-olds engaged not only in near generalization but also far generalization, applying adaptation by natural selection to predation scenarios more than a month later (Emmons et al., 2018). Finally, furthering the longer-range goal of leveraging an understanding of the uncontroversial topic of within-species adaptation into a progressively deeper grasp of larger scale evolutionary changes, follow-up research suggests that the mechanistic insight promoted in children is sufficiently abstract for many 7- to 8-year-olds to be able to accurately deploy it to understand and generalize the profoundly challenging concept of speciation (Ronfard, Doncaster, Brown, & Kelemen, 2018).

These developmental findings are preliminary, of course, and derive from small-scale interventions rather than fully elaborated spiraling classroom curricula. Nevertheless, they demonstrate young children's capacities to accurately grasp complex and foundational counterintuitive mechanisms by at least the second grade. They also converge with other findings suggesting that, when offered instruction that scaffolds the construction of coherent mechanistic frameworks and models, young children can elaborate and apply accurate theories of various pivotal counterintuitive phenomena (e.g., Lehrer & Schauble, 2012; Nguyen, McCullough, & Noble, 2011). Second graders, for example, can learn and use coherent particulate conceptions of matter that not only run counter to their macroscopic perceptual experiences but also to their teleological and essentialist intuitions about materials (e.g., "matter only exists if it has a function, and phase changes reflect different material kinds"; Samarapungavan, Bryan, & Wills, 2017; for other suggestive evidence, see Haeusler & Donovan, 2017; Stein, Hernandez, & Anggoro, 2010).

Furthermore, similar explanation-based interventions have been found to influence not only children's reasoning within the classroom but also their behavior outside of it: For example, third graders who were taught a coherent mechanism of germ transmission—one involving the counterintuitive causal notion that unobservable bacteria and viruses are alive—not only made accurate inferences about risky health behaviors but also were more likely than control groups to actively wash their hands before food preparation (Au et al., 2008; Weisman & Markman, 2017). Likewise, kindergarteners made healthier snack choices after hearing storybooks presenting a coherent theory of nutrition (Gripshover & Markman, 2013; see also Nguyen et al., 2011). Thus, a body of evidence is slowly accumulating to support the idea that carefully constructed, coherent causal-explanatory instruction in early elementary school is both viable and productive for children. Although it would be naive to view this general approach as representing a panacea to enduring science misconception, results to date certainly invite serious consideration of both its short- and long-term benefits. For information on the curricular materials described in this article, please visit http://www.evolvingmindsproject.org.

Conclusion

From early in development, human beings develop intuitive explanatory frameworks that form the root of scientific misconceptions, frameworks that are often later suppressed but rarely erased. As a result, they enduringly influence learning and compete for cognitive resources during moment-by-moment reasoning. The argument here is that we can therefore think about learning counterintuitive scientific ideas as akin to becoming a fluent speaker of a second language, a task that becomes increasingly difficult the longer it is delayed and one that is almost never achieved with only piecemeal instruction and infrequent practice. Thus, the current proposal is that we should start earlier in helping children become fluent and coherent scientific thinkers, and we should structure instruction that—while tuned to attentional and memory limitations—leverages their interest in explanation and their abilities to reason in abstract, causal terms. In short, children deserve early formal science instruction that is at once interesting and comprehensively explanatory, offering unifying causal mechanisms and principles that provide a lifelong foundation for making sense of a broad range of potentially disparate phenomena. Although the practical aspects of implementing such explanation-based instruction are nontrivial, in a global climate of increasing emphasis on scientific literacy and science-education reform (e.g., NGSS), the challenges also do not seem insurmountable. As with any new approach, careful consideration is required for a range of issues, including professional development strategies for nonspecialist elementary educators that not only address content and pedagogical knowledge but also motivational factors such as science anxiety. In the latter case, creative use of simple pedagogical tools such as explanatory picture storybooks may have a significant role to play because one benefit of their integration into classroom practice is that they reduce demands on elementary teachers to consistently operate as a primary source of explanatory expertise.

In suggesting that we focus on pivotal explanatory mechanisms from earlier in schooling, it is also worth returning again to what the present argument is not. First, by acknowledging that young children are far more capable as causal-explanatory thinkers than we often credit them for being, this is not an argument that they have detailed theoretical commitments rather than more general explanatory frameworks (diSessa, 2008) or, importantly, that their explanatory competences should push the teaching of any and all complex ideas earlier simply because it might be possible. On this latter point, the academic demands of elementary-school educations in many countries are often already substantial. Rather than suggesting that we add to these expectations, the current proposal is that by focusing on a select set of unifying mechanisms most prone to later theoretical misconceptions, we actually decrease demands on children—demands created by teaching them a patchwork of unexplained descriptions or isolated cause-and-effect ideas.

In turn, the proposed approach will give children explanatory power that may not only act as a prophylaxis to error during online scientific reasoning over time but also feed children's early-developing and often thwarted drive for explanation. Given the dual-processing evidence that intuition-based frameworks persist rather than get replaced, it is not expected that helping children to elaborate such scientific explanations would eliminate any of the benefits of common-sense intuition to their everyday reasoning. By contrast, it is envisaged that shifting the focus to a constrained set of satisfying pivotal explanations from elementary school might help to curb the well-documented drop-off in science interest that occurs in adolescence, when science teaching tends to begin in earnest and students are suddenly overwhelmed by a barrage of complex information (e.g., Haeusler & Donovan, 2017; Potvin & Hasni, 2014). In sum, the early-elementary science-curriculum proposal here emphasizes generalizable mechanistic explanation over description, depth over breadth, and fewer pieces of information—not more. In theory, such streamlining should also significantly reduce the demands on teachers, particularly if standardized-assessment expectations—in regions that emphasize these for elementary science—follow suit.

Second, the proposal that we can use tools, such as storybooks, to teach young children about unobservable, pivotal processes is not a call for a return to pedagogical approaches that are based on direct instruction or authoritarian "telling" rather than on children's active inquiry learning of scientific principles. Indeed, the coherent theory-based approach advocated here encompasses the strengths of both direct instruction and inquiry learning in a guided-inquiry framework (Klahr, 2009; Weisberg, Hirsh-Pasek, Golinkoff, Kittredge, & Klahr, 2016). For example, in addition to capitalizing on an enjoyable joint attentional read-aloud storybook context, the brief storybook interventions of Kelemen et al. (2014) rely heavily on children's self-generated explanations as a mechanism of domain-specific learning and generalization. This, in turn, yields an explanatory basis from which students can engage in hypothesis testing as they actively explore and interpret exploratory outcomes. Likewise, activities such as generating and manipulating models of atomic structure remain core to explanatorily coherent inquiry-based interventions focused on the particulate structure of matter, even as it is also noted that, as with any instruction, the models and activities can themselves sometimes promote misconceptions—outcomes that should be anticipated as early as possible (e.g., Haeusler & Donovan, 2017; Samarapungavan et al., 2017; see also Lehrer & Schauble, 2012; Vosniadou, 2013).

In conclusion, many insights into the methods that facilitate student learning have been accrued in the education and learning sciences over the past 3 decades. These methods include increasing the coherence of text, prompting students to explain scenarios, retrieve information, and compare across contrasting cases (Mayer & Alexander, 2017). During this same period, the cognitive and developmental sciences have produced substantial insights into young children's explanatory and theory-building abilities, their interest in and capacities for abstract domain-specific explanation, and the early emergence and persistence of intuition-based explanatory frameworks. Global challenges and economies increasingly demand a scientifically informed population. In that context, this article calls for a closer marriage between scholars in these research disciplines and early-education practitioners, in the service of greater enduring scientific understanding for all.

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