Science v. Intuition

Why It Is Difficult for Scientific Knowledge to Take Root

BY ANDREW SHTULMAN

Scientific discoveries come in two forms: those that can be understood in terms of a preexisting paradigm and those that require the adoption of a new paradigm altogether. Consider the difference between the discovery of Neptune and the discovery of heliocentrism. Neptune was predicted to exist many decades before it was discovered, on account of the fact that its mass caused known, but unexplained, perturbations in the orbit of Uranus. Nineteenth century astronomers thus sought observational confirmation of an eighth planet with the same basic properties as those of the seven planets already known to exist. When Neptune was observed in 1846, its existence was readily assimilated into astronomers' preexisting model of the solar system. That model itself, however, was hard won.

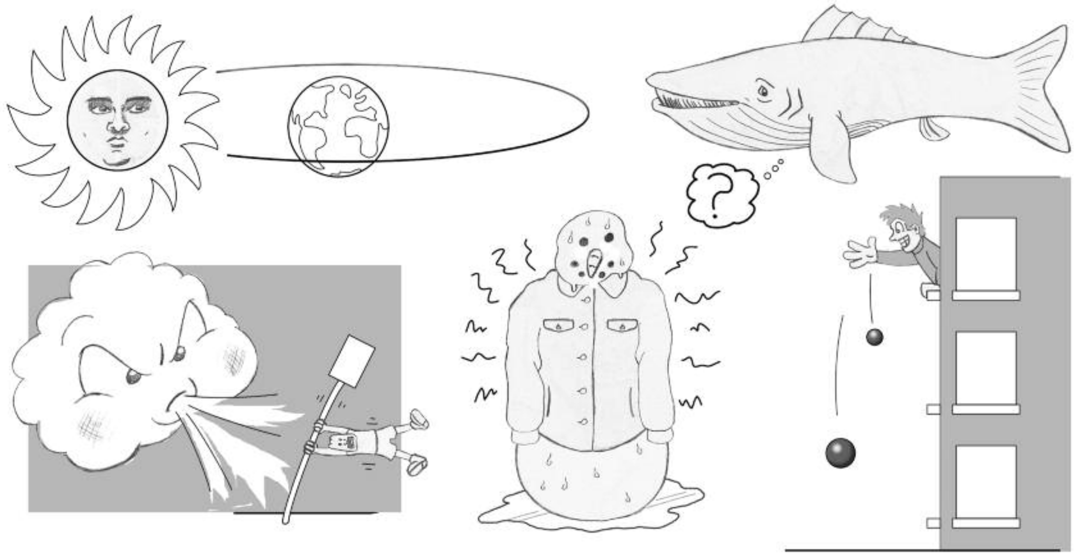
Prior to the acceptance of heliocentrism, astronomers typically subscribed to geocentric models of planetary motion that differed from heliocentric models not only in what they identified as the center of the universe but also in what they considered planets to be (balls of other-worldly ether), what they considered stars to be (fixed points of light on a rotating sphere), and how they explained planetary motion (as caused by the planets themselves). Accepting the sun as the center of planetary motion thus required revision of the most basic astronomical assumptions of the time.

Like scientific discovery, the process of learning science also comes in two forms: learning that can be accomplished in terms of preexisting concepts, termed by psychologists as *knowledge enrichment*, and learning that requires the adoption of new concepts altogether, termed *conceptual change*. Both forms of learning occur in every domain, but knowledge enrichment is far more common and far easier than conceptual change. In astronomy, learning the names and locations of the planets would constitute knowledge enrichment, whereas learning why planets revolve around stars or how planetary motion causes such phenomena as tides or seasons would constitute conceptual change. In physics, learning the value of physical constants like the speed of light or the rate of acceleration due to gravity would constitute knowledge enrichment, whereas learning why all objects fall with the same acceleration or how acceleration is related to force and velocity would constitute conceptual change. In biology, learning the traits of unfamiliar organisms would constitute knowledge enrichment, whereas learning how organisms are related by common ancestry or how traits arise by natural selection would constitute conceptual change.

Can Scientific Knowledge Overwrite Intuition?

For over three decades, researchers in the fields of cognitive psychology, developmental psychology, and science education have been studying the dynamics of conceptual change. They have been characterizing what we intuitively know about different domains, how that knowledge differs from scientific knowledge, and how that knowledge changes with instruction, either formal instruction in the classroom or informal instruction at home or elsewhere (e.g., museums, libraries, parks). While different researchers have analyzed conceptual change in different ways, most would agree that conceptual change requires a basic *restructuring* of one's intuitive knowledge. That restructuring could involve collapsing distinctions that are no longer meaningful on a scientific conception of the domain (e.g., collapsing the distinction between objects in motion and objects at rest), introducing new distinctions that *are* scientifically meaningful (e.g., making a distinction between weight and mass), or moving an entity from one mental category to another (e.g., shifting the entity *air* from the category *space* to the category *matter*). Accumulating new facts and new experiences is not sufficient to bring about conceptual change; one must instead reorganize the very nature of one's understanding.

Because conceptual change requires knowledge restructuring, it has long been assumed that, once the restructuring was complete, one's initial conceptions of the domain would no longer be accessible. Restructuring one's knowledge was assumed to erase previously held intuitions in the same way that remodeling one's house erases previ-



ously navigated floor plans. A growing body of research, however, suggests that conceptual change does not produce this result. Rather, conceptual change appears to produce *dual* modes of understanding: a new scientific understanding of the domain and an older, more intuitive understanding of the domain that coexists with, but is not replaced by, the scientific understanding. Put differently, adults with extensive science education appear to harbor intuitions that they had explicitly rejected many years prior—intuitions like "whales are fish," "coats produce heat," "the wind is alive," "air has no weight," "heavier objects fall faster than lighter objects," and "the sun revolves around the Earth." In some cases, these intuitions had previously been documented only among preschool-aged children, but, with the application of new methodologies, they are now being documented among scientifically literate adults as well.

Animist Intuitions Across the Lifespan

One of the best studied cases of the coexistence of science and intuition is that involving conceptions of what is and is not alive. Beginning with Jean Piaget, developmental psychologists have long observed that young children conflate *life* with *animacy*. Not only do young children attribute life to non-living but animate entities like the sun and the wind, but they also deny life to living, yet relatively inanimate, entities like flowers and trees. By age eight, this pattern of attributions is typically replaced by a more biologically informed pattern—life is now identified with metabolic processes (e.g., eating, drinking, breathing, growing) rather than mobility. It is this conception of life—life as the end-product of a set of interrelated metabolic functions—that forms the basis of the adult's understanding of biological phenomena in most cultures today.

Illustrations by Daniel Parrish

Nevertheless, the adult conception of life gives way to the child-like conception when adults are tested under conditions that are speeded up. In one study, the psychologists Robert Goldstein and Sharon Thompson-Schill asked adults to judge the life status of a variety of entities, including animals (e.g., pigs, sharks), plants (e.g., orchids, elms), non-living animate objects (e.g., comets, rivers), and non-living inanimate objects (e.g., brooms, towels). They found that adults, like young children, were more likely to err on plants (judging them not alive) and animate objects (judging them alive) than on animals and inanimate objects, and, if they judged the life status of plants and animate objects correctly, it took them significantly longer to do so than to judge the life status of animals and inanimate objects.

Animistic intuitions reemerge not only when adults are placed under speeded up conditions but also when they sustain permanent cognitive impairments, such as those produced by Alzheimer's Disease. The psychologists Deborah Zaitchik and Gregg Solomon have recently documented a variety of forms of animistic thinking among Alzheimer's patients. When Alzheimer's patients are asked what it means for something to be alive, they are more likely to cite motion as a prerequisite for life than to cite genuinely biological properties, like eating or breathing. Healthy elderly adults, on the other hand, are more likely to cite biological properties than to cite motion. When Alzheimer's patients are asked to provide examples of things that are alive, they almost always mention animals but rarely mention plants. Healthy elderly adults, on the other hand, almost always mention both animals and plants. And when Alzheimer's patients are asked to judge the life status of entities presented to them, they tend to err in exactly the same ways as young children, judging the sun and the wind as alive but judging flowers and trees as not alive (even without time restrictions). Healthy elderly adults, on the other hand, continue to provide a biologically informed pattern of judgments. The cognitive impairments wrought by Alzheimer's Disease appear to allow animist intuitions to reemerge that have coexisted with a more scientific conception of life for decades but have hitherto been suppressed.

Teleological Intuitions Across the Lifespan

Similar findings have been documented in the domain of teleological reasoning. Teleology is the study of design in nature, and teleological explanations are explanations that appeal to something's design, or purpose, as its reason for existence. For instance, a teleological explanation for why there are kidneys is that kidneys filter blood; the alternative to a teleological explanation is a mechanistic one—e.g., that kidneys exist because ancient organisms with kidneys (or proto-kidneys) left more offspring than those without kidneys. The psychologist Deborah Kelemen has shown in numerous studies that children are more "promiscuous" with their teleological explanations than are adults. Whereas both children and adults will provide teleological explanations for human artifacts (e.g., pencils exist for writing, stoves exist for cooking) and for biological parts (e.g., ears exist for hearing, lungs exist for breathing), only children will provide teleological explanations for whole organisms (e.g., birds exist for flying, bees exist for making honey) and for naturally occurring objects (e.g., clouds exist for raining, lakes exist for swimming). Children become more selective in their teleological explanations by early adolescence, but that selectivity is tenuous. When college-educated adults are asked to judge the acceptability of teleological explanations under speeded up conditions, they tend to accept unwarranted explanations, like "birds exist for flying" and "clouds exist for raining," which they do not accept under normal (non-speeded) conditions and presumably have not accepted under such conditions for many years.

Moreover, just as Alzheimer's patients endorse animistic conceptions of life explicitly endorsed only by children, they also endorse teleological conceptions of nature explicitly endorsed only by children. In one study the psychologist Tania Lombrozo and her colleagues provided Alzheimer's patients with both mechanistic and teleological explanations for a variety of natural phenomena, some of which warranted a teleological explanation (e.g., eyes exist "so that people and animals can see") and some of which did not (e.g., rain exists "so that plants and animals have water for drinking and growing"). Compared to healthy elderly adults, Alzheimer's patients were not only more likely to judge unwarranted teleological explanations as acceptable but were also more likely to judge those explanations as *preferable* to mechanistic ones. These findings suggest that teleology, like animism, is a deep-seated form of intuition that can be suppressed by a more scientific worldview but cannot be eradicated altogether. If such intuitions could be eradicated, Alzheimer's patients should show no signs of animism or teleology, as they have typically had over 60 years of experience operating on the basis of a more scientific worldview prior to the onset of their disease.

Neurological Evidence of Resilient Intuitions

The coexistence of science and intuition has been documented not only at the level of behavior but also at the level of the brain. The psychologist Kevin Dunbar and his colleagues have used functional Magnetic Resonance Imaging (fMRI) to determine whether college-educated adults exhibit different patterns of brain activity when watching motion displays that were consistent or inconsistent with the laws of physics. The physics-consistent displays depicted two balls of unequal size falling to the ground at the same rate; the physics-inconsistent displays depicted the larger ball falling to the ground at a faster rate than the smaller ball. Previous research in science education has shown that physics novices expect larger objects to fall faster than smaller objects, so the physics-inconsistent displays accorded with naïve intuitions but the physics-consistent displays did not. Dunbar and his colleagues found that, among participants who judged the physics-consistent displays as natural and the physics-inconsistent displays as unnatural (the correct pattern of judgment), watching those displays increased activation in an area of the brain associated with error detection and conflict monitoring: the anterior cingulate cortex. That is, participants who exhibited no behavioral evidence of holding the misconception "heavier objects fall faster than lighter objects" still exhibited neural evidence of holding that misconception insofar that their brains appeared to be detecting and inhibiting intuitions to the contrary.

Education researcher Patrice Potvin and his colleagues have documented similar results in the domain of electricity. In one study, they showed physics experts and physics novices electric circuits that were either complete or incomplete and asked to participants to determine whether a light bulb that was part of the circuit should or should not be lit. Participants performed this task while their brains were being scanned by an fMRI machine. At the behavioral level, the physics experts were perfectly able to discriminate correct configurations (complete circuits with lit bulbs, incomplete circuits with unlit bulbs) from incorrect configurations (complete circuits with unlit bulbs, incomplete circuits with lit bulbs), indicating no evidence of the misconception that every physics novice in the study revealed, namely, that connecting an electric device (a light bulb) to an electric source (a battery) will cause that device to activate regardless of whether the circuit is complete. The fMRI data, however, told a different story. Physics experts showed significantly more activation in their anterior cingulate cortex and other areas associated with conflict monitoring than did physics novices when evaluating the scientifically incorrect circuits. Apparently, the misconceptions explicitly endorsed by physics novices were still represented in the brains of the physics experts, causing conflict in situations relevant to those misconceptions.

Resilient Intuitions are the Rule, not the Exception

Research from my own lab has shown that tensions between science and intuition are not limited to the handful of misconceptions noted above—i.e., that life is synonymous with animacy, that everything in nature exists for a purpose, that heavier objects fall faster than lighter objects, and that a single wire is sufficient to light a bulb. Rather, these tensions can be found in every domain of knowledge for which learning entails conceptual change (i.e., knowledge restructuring). The task we used to document such tensions was a statement verification task. Participants were are asked to verify, as quickly as possible, two types of scientific statements: statements that are consistent with intuition (e.g., "the moon revolves around the Earth," "heat increases an object's temperature," "genes that code for eye color can be found in the eye") and statements involving the same concepts but that are inconsistent with intuition (e.g., "the

Earth revolves around the sun," "heat increases an object's size," "genes that code for eye color can be found in the liver"). The logic behind this design is that if naïve intuitions survive the acquisition of contradictory scientific knowledge, then the latter should cause greater cognitive conflict than the former, resulting in (a) slower verifications and (b) less accurate verifications.

Using this method, my colleagues and I have documented evidence of long-term conflict between science and intuition in ten different domains of knowledge: astronomy, evolution, fractions, genetics, germs, matter, mechanics, physiology, thermodynamics, and waves. What is particularly remarkable about these findings is their robustness. Our task probed for conflict between science and intuition with respect to 50 different concepts—5 concepts per domain across 10 domains—and we observed such conflict for 43 of the 50 concepts. We also observed conflict both for statements that are scientifically true but intuitively false (e.g., "air is composed of matter," "humans are descended from sea-dwelling creatures") and for statements that are scientifically false but intuitively true (e.g., "fire is composed of matter," "humans are descended from chimpanzees"), indicating that the conflict is true of both positive misconceptions and negative misconceptions.

Furthermore, the participants in our studies have typically taken more science courses than the average American—three or more college-level math and science courses, not to mention four to six years of middle-school and high-school science courses—and virtually all participants showed the effect. Indeed, those who were most accurate at distinguishing scientifically correct statements from scientifically incorrect statements showed the greatest degree of conflict between science and intuition. The robustness of this phenomenon across domains, concepts, statements, and participants suggests that it reflects more than just a handful of stubborn misconceptions. Rather, it appears to reflect a fundamental property of conceptual change, namely, that intuition can be *overridden* but not *overwritten*.

Why are Naïve Intuitions so Resilient?

One explanation for why intuition survives the acquisition of contradictory scientific information is that the scientific information itself has not been well learned. The state of science education in the U.S. is notoriously poor, as it is in many other countries as well. Might widespread educational inadequacies be responsible for the aforementioned effects? At least one source of data suggests not: professional scientists are no more immune to the conflict between science and intuition than are non-scientists. Under speeded conditions, professional biologists reveal animistic intuitions of the same sort revealed by non-biologists (e.g., that comets are alive and orchids are not), and professional physicists endorse unwarranted teleological explanations of the same sort endorsed by non-physicists (e.g., that rain exists so that animals have water for drinking). In my own lab, we have found that science professors with three or more decades of career experience were no faster on our statement-verification task than were the college undergraduates in their courses. That is, science professors continued to verify intuition-inconsistent statements significantly more slowly than intuition-consistent statements across several domains of science, including their own.

The question thus remains: why are naïve intuitions so resilient? One possibility that we are currently investigating in our lab is that such intuitions are sustained and enforced by how we talk about natural phenomena in everyday discourse and how we perceive natural phenomena in everyday situations. Much of our colloquial language seems to be predicated on intuitive conceptions. For instance, the terms "sunrise" and "sunset" imply that the day/night cycle is caused by movements of the sun rather than movements of the Earth. More accurate terms would be "sun accretion" and "sun occlusion." Likewise, the terms "warm coat" and "cold wind" imply that heat is a property of specific objects or substances rather than a property of an entire system. More accurate terms would be "insulating coat" and "disequilibrating wind." Our perceptual experience is no less misleading. Coats *feel* as if they produce heat, and the sun *looks* as if it moves across the sky. If language and perception are indeed responsible for the persistence of naïve intuitions, then it may be possible to design learning environments that minimize their effects, at least during instruction. Moreover, making students aware of the limitations of everyday language and everyday perception may help them distinguish judgments based on scientific knowledge from those based on intuition. While science may always coexist with intuition—either for reasons of language and perception or for other reasons altogether—awareness of that coexistence may provide at least some immunity to the sway that intuition holds over attitudes and decisions that would be better informed by science. S