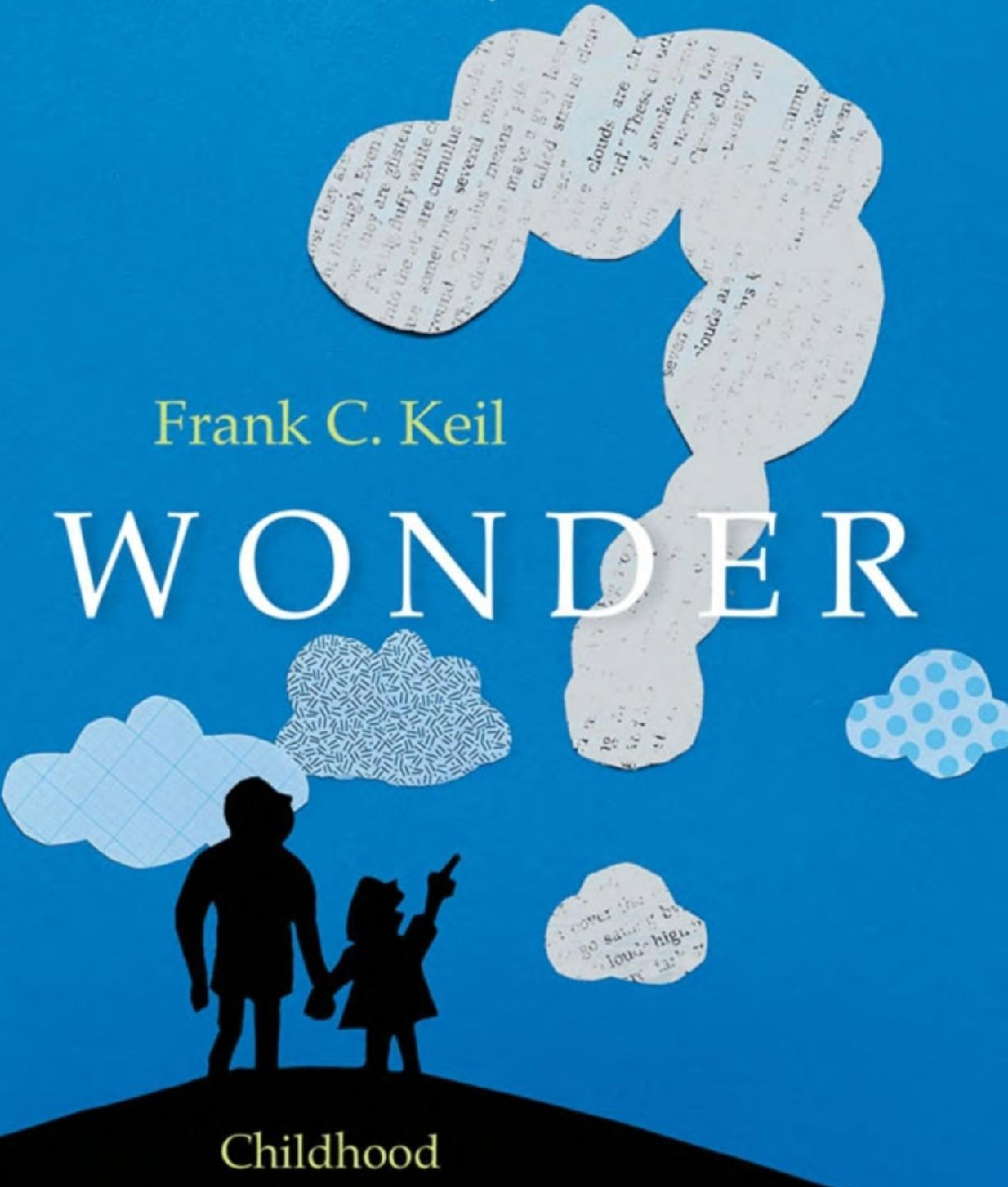
"Frank Keil is among the deepest thinkers about thought, and here he explores the wondrous urge that drives our lifelong quest to understand the world."
—STEVEN PINKER, author of *Rationality*

Frank C. Keil

WONDER



Childhood and the Lifelong Love of Science

The MIT Press would like to thank the anonymous peer reviewers who provided comments on drafts of this book. The generous work of academic experts is essential for establishing the authority and quality of our publications. We acknowledge with gratitude the contributions of these otherwise uncredited readers.

This book was set in Stone Serif and Stone Sans by Westchester Publishing Services.

Library of Congress Cataloging-in-Publication Data

Names: Keil, Frank C., 1952– author.
Title: Wonder : childhood and the lifelong love of science / Frank C. Keil.
Description: Cambridge, Massachusetts : The MIT Press, [2022] |
Includes bibliographical references and index.
Identifiers: LCCN 2021007025 | ISBN 9780262046497 (hardcover)
Subjects: LCSH: Cognition in children. | Reasoning in children. | Intuition. |
Science—Study and teaching.
Classification: LCC BF723.C5 K424 2022 | DDC 155.4/13—dc23
LC record available at https://lccn.loc.gov/2021007025

Contents

Preface

When our children were young, we lived in a house on the edge of a cliff overlooking Cayuga Lake, in Upstate New York. As we went up and down the ninety-eight (!) stairs to the lake, little bits of the shale cliff would break off and land on the stairs, much of the time revealing small fossils: shells, trilobites, leaves, and other mysterious patterns etched in stone. These attracted the curiosity of all our children making their way up and down the stairs as toddlers. They soon noticed that those patterns implied the presence of something more than an inanimate rock, something that suggested life. They would ask, "What is that?" "Why is it there?" "What happened to it?" and "How did it last so long?" Each of our attempts to provide an answer usually triggered a follow-up question. In those days before search engines, we'd run to our multivolume 1929 *Encyclopedia Britannica* we'd bought at a yard sale and look for answers, or sometimes we'd call relevant colleagues at Cornell. Our entire family fondly remembers those times even now more than thirty years later. As we will see, a tremendous amount of cognitive activity was occurring in those seemingly simple events, activity that reveals children's powerful propensities for learning about their world.

This book describes a convergence of major advances in recent research on children's minds. Those advances reveal an extraordinary cluster of early emerging abilities that help explain this youthful wonder and joy of discovery. We see preschoolers and even infants as driven to learn not just facts and images of their world but also underlying causal patterns that are at the very heart of science. Infants start with certain foundational contrasts between broad domains, such as the social and the nonsocial, that become greatly elaborated during the preschool and early school years. They learn not just as individuals but also as members of knowledge communities and show impressive early senses of how to best "harvest" knowledge from these communities and how to best engage with other minds.

Yet those joyous youthful moments of discovery and engagement often fade as children grow older, cease to wonder about the world, and stop building new understandings. I describe in detail how this decline occurs and argue that it is neither inevitable nor desirable. The new findings about children's natural cognitive inclinations show how an early love of science can be sustained throughout one's life with enormous attendant benefits. When we no longer enjoy wondering and searching for answers, we fail to expand our grasp of the world. We may never learn even the most basic causal processes that give insight into the workings of devices and the natural world. We digest food and unlock doors with no grasp of what happens within that makes digestion and unlocking possible. Even worse, we often are not even aware of how little we know and become ever more vulnerable to misunderstanding and manipulation by others.

In a world of ever more dizzying discovered and engineered complexity, it might seem that we all have to surrender our agency and just passively rely on others without any real sense of what they know and why. I argue against such a view in the three parts of this book.

First, I describe the extraordinary cognitive abilities of young children and preverbal infants. I show how these young humans have a diverse set of talents for making conjectures about how things work and how they are driven to expand on their initial understandings through engaging in individual explorations, through accessing what others know and by sensing what kinds of causal patterns and structures are likely to be especially informative. Young children possess many of the critical precursors to mature scientific thought as well as the passion for exploration and discovery that we associate with model scientists.

Second, I show how the glorious rise of wonder in the early years can be stifled and distorted into paths where the desire to discover fades away. I will describe seductive but mistaken views of young minds and their motivational processes. I then show how these misunderstandings can lead to disastrous declines of spontaneous exploration, conjecture, and questioning during the early school years and beyond. None of these are inevitable, but they happen all too often.

Finally, in the third part, I describe how suppressing wonder leads to drastically different futures from cases in which it is encouraged and supported.

I'll describe bleak lives of disengagement from science accompanied by distrust and denialism. I'll show how these orientations can be fueled by cognitive biases and motivated intellectual blind spots. Ultimately, such stances toward science lead to dogma and distortion that corrupt our understandings of all that is around us. I'll then describe a different path illuminated by the lives of a few inspirational individuals who never stop wondering and reveling in the successive discoveries that made their daily experiences ever deeper and more rewarding. I'll show how those positive cognitive habits that we all possessed as children can be reawakened to benefit not just ourselves but also society at large. By better understanding how illusions and social influences can derail us and make us more susceptible to cognitive biases and negative attitudes toward science, we can see how different, more rewarding paths are also possible. We can become more like children, continuously experiencing a genuine joy in discovery and preferring activities that enable us to better grasp causal structure to simply being attracted to the mere appearances of pretty things.

When we reawaken these early cognitive habits, we stop being alienated from science, ignorant of basic models, and sometimes openly hostile to the scientific community. By building on children's natural cognitive proclivities, we can avoid traps that lead to alienation and ignorance. We become much more able to combat the ever-rising tide of disinformation and to participate more fully in important policy decisions relating to science and technology. In the broadest sense, I argue that reengagement with science is critical to our individual and collective futures.

I am also ever in debt to another leading scholar in the humanities, Katie Lofton, a riveting scholar of religion and history and an inspirational dean of humanities at Yale. In a chance hallway encounter, I mentioned I was working on this book and she cheerfully asked to see it. I sent a late draft assuming that in the midst of the COVID-19 crisis it would vanish under piles of correspondence about remote teaching, social distancing and departmental affairs. Yet, somehow, only a few weeks later, Katie provided extraordinarily helpful comments that greatly influenced the final draft.

I thank Laura Kang, current principal of East Woods School, for spending many hours going through school archives so as to provide me with fascinating details about my remarkable science teacher more than half a century earlier. Many thanks as well to Vavara Petrolova for her knowledge about the Sputnik era from a Russian perspective and for researching Soviet archives that I could never access or read.

I will always be ever in debt to all past and present members of my extended lab group from postdocs to undergraduates to lab managers to summer interns. There are too many to list here, but they have all been enormously important colleagues who have shaped my ideas in so many different ways over the years. I simply could not have traveled this road of research and scholarship for the past four decades alone and acknowledge here their many contributions. Whenever I describe a study using the pronoun "we", I am indicating the involvement of others, often in key roles. Their names are well represented in the many endnotes.

I thank three anonymous reviewers of an early stage of this book, whose detailed suggestions on every chapter were invaluable in guiding my later writing. I am also especially indebted to two reviewers of the near final draft manuscript who made immensely helpful and detailed comments on every chapter.

Some of the material in this book is based on work supported by the National Science Foundation under (NSF grant DRL 1561143). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation. Within NSF, I express special thanks to the EHR Core Research (ECR) program and its visionary and passionate leader Gregg Solomon. I am also grateful to the National Institutes of Health, the Templeton Foundation, and the McDonnell Foundation for funding my research and interdisciplinary meetings. As with NSF, my writings here do not necessarily reflect the views of those funders. I am especially grateful to two inspirational leaders of the McDonnell Foundation, John Bruer and Susan Fitzpatrick, who for more than thirty years have provided me with incredible opportunities to acquire important new perspectives on cognitive science, learning and education.

Finally, I thank many people at the MIT Press. Ever since my undergraduate days at MIT, the Press has been an essential part of my career growth as a cognitive scientist. Press director Amy Brand and senior editor Phil Laughlin have been longtime colleagues in other projects, and I was delighted when they expressed an interest in this book. Phil has been brilliant in his choice of the anonymous reviewers and in his feedback on various drafts. I am especially grateful to Deborah Cantor-Adams, associate managing editor, and to Regina Gregory for clarifying and insightful edits. I am also grateful to the many contributions of the other members of the magnificent MIT Press team: Alex Hoopes, assistant acquisitions editor; Molly Seamans, designer; Sean Reilly, art coordinator; Tori Bodozian, production coordinator, and Heather Goss, publicist. Finally, many thanks to my thoughtful indexer, Tobiah Waldron.

1 The Cognitive Gifts of Childhood

1 The Puzzle and the Promise

The Rise and Fall of Wonder

A few miles from our house a celebrated independent bookstore carries a large collection of new books and old classics. What books do the store's well-educated clients buy? Roughly half the top sellers are nonfiction. On the nonfiction list, usually, at most, one book focuses on science. In national science best-seller lists, books in the top twenty rarely explain mechanisms, arguably the core product of science. Instead, we find biographies and self-help guides. Highly ranked "science" books often turn out to be attacks on science, branding research as deceitful, racist, misogynist, and corrupt. In October 2019 the ten bestselling "science and math" books on such lists included a diet regime, an analysis of how media falsely slandered the US president, and a guide on how to age more slowly. All of these last three books may have provided valuable information, but they definitely did not provide insights into underlying mechanisms or causal principles. The most traditional science topic covered in the top ten was a Cat in the Hat book on the solar system meant for kindergartners. Expand the list to the top twenty science and math books and we find an analysis of White people's difficulties talking about racism, techniques of psychotherapy, a guide for how to unleash our infinite potential and how to take a journey with the untethered soul. To be sure, other books in the top twenty did focus on more traditional science topics such as the history of humans, social and cognitive psychology, and a beautiful "illustrated exploration" of facets of chemistry. Even then, surprisingly little content provides causal explanations of the natural and engineered worlds. More broadly, in the top ten best-selling books in all areas for the past ten years on some lists, passion for science, captured the centrality of wonder beautifully in a 2019 interview:

> For me, I wanted to know how the world works. Every child wants to know how the world works. . . . That's the point at which we really need to connect . . . : honoring and respecting and integrating that incredible curiosity. Children come out picking up bugs and looking at things and trying to experiment, and that's how they learn about the world. . . . one of the issues that can happen in education is we actually destroy that [curiosity]. We want a specific answer. We ask for something to be memorized. And that's not the best way. . . . our goal is to harness that innate construct for information gathering and problem-solving and to refine it.[4]

In 1979, the psychologist Margaret Donaldson published a landmark book straightforwardly entitled *Children's Minds*.[5] She showed through clever experiments and elegant arguments how rigid stage theories were mistaken. Young children were not trapped in conceptually shallow early stages of thought that made some forms of understanding and insight unavailable. This book was one of the first and most powerful arguments leading to a revolution in the study of cognitive development. It is also an affirmation of an early drive to wonder. Near the end of the book, Donaldson described this early drive as plummeting when children enter school. In a later paper, she described the problem as arising from a "mismatch between school and children's minds."[6] Unfortunately, the mismatch and its corrosive effects on wonder continue, just as Donaldson implied. As I write this just a few months after Donaldson's death at age ninety-four, I am hoping we may finally confront the mismatch.

Wonder

The word *wonder* first appeared in Old English around AD 675 in a hymn by Cædmon, an allegedly illiterate cow herder from what is now southern Scotland.[7] Cædmon's wonder (wundor or uundra in Old English) implied an awe of the natural world, including humans. Awe remains a theme in many uses of wonder up to the present, but wonder in our sense means something more than awe. Awe alone often is passive—verging on the meaning of dumbstruck or stupefied reverence. We'll use the more active meaning of wonder described by the *Oxford English Dictionary* (OED) as "desirous to know or to learn." Wonder is a drive that comes from within. Richard

Holmes, known for his biographies of romantic poets and his book *The Age of Wonder: How the Romantic Generation Discovered the Beauty and Terror of Science*, describes wonder as having varied meanings that keep evolving over the ages, but he constantly returns to the idea of a childlike passion to know and explore. Changes in in the meaning of wonder often include shifts in moral implications. For example, historians of science Lorraine Daston and Katherine Park describe a dizzying array of dramatic changes in meaning and moral tone from 1150 to 1750.[8]

Today, wonder has different senses concerning its manner of engagement with science. Lisa Sideris, a scholar of religion, science, and the environment, describes one view of wonder as the means for revealing with stark clarity the story of the universe. Sideris sees this view as leading to arrogance and a feeling of human mastery over the world.[9] She favors instead a sense embodied in the naturalist's Rachel Carson's writings, one of humility and increasing mystery as each new discovery revealed even deeper puzzles.[10] Given such multiple senses and connotations, we need to specify the particular meaning intended here, a meaning that is closely connected to how young children learn about the world.

Wonder is not the same as curiosity.[11] Curiosity often means a desire to know "What's next?" or "What is that missing thing?" Curiosity about facts is also different from the sense of wonder intended here. Curiosity about facts often leads to a simple answer and then a dead end. For example: Q. What state has the most cars? A. California. (That ends the discussion.) Curiosity about cause and mechanism has cognitive legs and is closer to what we mean here by wonder. Most why and how questions lead to a potentially endless stream of follow-ups. Q. How do sunflowers move? A. Sunflowers turn their faces during their growth phase. They turn toward the sun in the morning and track it through the day. Q. How does that work? Q. Why does that occur only in growing sunflowers? A. . . . Causal mechanistic questions open up new territories of explanation. They arouse a sense of embarking on exciting journeys of discovery. Facts can sometimes do this as well by implying some kind of expanding information, but frequently they do not. Here, "wonder" describes a quest for understanding, which usually involves asking how and why. This is the most central motivating factor behind a lifelong interest in science. Instead of merely asking "What's next?" wonder also asks "Is it something like X or something like Y, or Z that is next?"

Wondering as intended here goes beyond merely being curious. Building on prior knowledge and some sense of major causal and spatial patterns, we entertain rough sketches of possibilities or interpretations and strive to learn which is more accurate and how it is filled out. To marvel at something is also linked to wondering. While marvels and wonders often refer to awe-evoking things, when children engage in wonder, they do much more than simply sit in a state of passive reverential awe.[12] Their awe is better described by Carson—a joyous marveling at how an insight has revealed an enormous new expanse of possible patterns to explore. It is not the dumbstruck, potentially fear-laden sense of awe experienced by adults. Almost a century ago, in an isolated region of Papua-New Guinea, the anthropologist Margaret Mead observed that, when children were asked to explain why a canoe tied to a tree drifted away overnight, they offered explanations of how the rocking boat gradually loosened up the knot. In contrast, many adults invoked spirits, moral transgressions, and supernatural interventions.[13] When we see young children's wonder as infused with supernatural agency, we impose the encultured interpretations of adults.

The child's wonder resembles the act of exploring a new environment. When backpacking in an alpine wilderness for the first time, as the terrain unfolds ahead, you "wonder" what is around the next bend and usually walk a bit faster to find out. You aren't expecting any one thing in particular; instead the terrain you have traversed and the surrounding scenery suggest structured possibilities: an alpine meadow with far-off views, a glade with a stream, a rocky moraine to traverse with caution. Your projections are constrained. You don't expect to see ocean surf, or a rain forest, or an amusement park. When Captain Cook rounded Cape Horn in his first voyage and sailed into the enormous Pacific, he wondered what he would discover, but his wondering had structured possibilities: a vast southern continent, a long peninsula sticking out from Asia, an impassable doldrums. He had some hints from his few European predecessors, but those only served to add gentle guidance to his wondering.

Wonder becomes more elaborated and thoughtful with each wonder-driven exploration. Expectations are fleshed out and suggest more structured possibilities. The ecologist Suzanne Simard, who discovered the fungal nets that link trees underground, first wondered about how they were interconnected and why. After learning that those nets were linked to nutritional support, she then expanded her wondering to how such connections were related to evolutionary theory and how they might pose riddles relating to theories of altruism.[14]

Our sense of wonder usually occurs in sentence frames such as "I wonder why . . . ," "I wonder how . . . ," or more generically "I wonder if . . ." or "I wonder whether . . ." It entails a tentative expectation or interpretation that wonderers are eager to confirm or discredit. It occurs not as a precise formal prediction but as an informed class of conjectures. Many of my intuitions about wonder arise from watching young children, especially our three sons and our granddaughter Frances. Frances, now at age two, has an insatiable hunger to explore and find out what is happening and why. In any new space, she immediately roams all over until she has a good sense of the layout (she is not shy). She quickly zeroes in on any new device or animal and immediately inspects it—not as the patient noninterfering invisible observer required in some anthropological field studies but rather in a headlong, grasping, groping, smelling, tweaking frenzy. She does everything she can to the new entity to learn more about it. We must initially limit these activities to save her, or the object, or both, from injury. With each successive encounter, she shows more tailored forays that acknowledge the risks associated with some objects (cats are not to be pounded).

These patterns of investigation are plentiful in all young children, as are the squeals of delight when a particularly exciting new feature is discovered. The drive to engage in activities that nourish wonder can be massive. Many times in the past few months, we have had to pull Frances away from one of these engagements to remind her that she is late for lunch, is ready for bed, or has to come inside from the snow. Her protests indicate an intellectual hunger that can trump physiological hunger, fatigue, and physical discomfort. Why should young children be endowed with such a drive when motivations relating to nutrition and shelter seem more important? Wonder, as meant here, gives a child a feeling of agency and self-efficacy. She not only learns more about the world and how things work but she learns more about how to do things to accelerate this understanding. She learns different ways of manipulating objects. She becomes skilled at accessing information in the minds of others. She discovers that the more she wonders about something and acts on that wonder, the more informative and gratifying that process becomes. Each new insight motivates more sophisticated conjectures.

Wondering builds and elaborates successive wondering. It is a perfect setup for creating an addiction to the process of discovery. When Frances first found our piano at eleven months, she was engrossed with how her pounding on keys produced sounds. Over the next several months, largely on her own, she has built on this insight to learn that parts of the key board produce high and low sounds, that individual keys make cleaner sounds than trios of adjacent ones, that pushing keys in certain orders makes especially pleasing sounds, and that some rhythmic-like patterning is involved. She is interested in how this all comes about inside the piano, but we haven't yet figured out how to let her safely explore the insides.

Our meaning of wonder is guided by observations of children and by descriptions of their behavior in the research literature. Wonder is an enabling and motivating process. It allows us to experience life more richly and imbues things with more meaning. This last point is controversial and was famously criticized in Keats's poem *Lamia*.[15] *Lamia* construes Newton's breaking down the components of light by using a prism as destroying the beauty and mystery—he "unweaves" the beautiful tapestry of the rainbow into homely brute physical components.

Mark Twain seems to echo Keats when he bemoans how serving as a pilot and learning all about how the river "works" ruined it another way:

> No, the romance and the beauty were all gone from the river. All the value any feature of it had for me now was the amount of usefulness it could furnish toward compassing the safe piloting of a steamboat. Since those days, I have pitied doctors from my heart. What does the lovely flush in a beauty's cheek mean to a doctor but a "break" that ripples above some deadly disease? Are not all her visible charms sown thick with what are to him the signs and symbols of hidden decay? Does he ever see her beauty at all, or doesn't he simply view her professionally, and comment upon her unwholesome condition all to himself? And doesn't he sometimes wonder whether he has gained most or lost most by learning his trade?[16]

Twain, however, may be describing two phenomena here. He offers the idea of deeper understanding displacing beauty, but he may be also alluding to a different effect—how intrinsic interest can become undermined, or how play can be turned into work. Motivational factors can both suppress and support spontaneous enjoyment, and Twain has returned to that theme again and again in his other writings. Keats may also sometimes intermingle how joyful play can be corrupted by work with the idea that beauty and awe are ruined by science. It is quite easy to confuse one for the other. Keats's views of science were also more nuanced than suggested by and thirties, he gave lectures to the public at the Royal Institute and the Royal Society in London. The lectures were usually open to everyone, which mostly meant a mix of the aristocracy and the middle class (few paupers attended). But for its time, it was an extraordinary opening up of science to much broader audiences of nonscientists that extended far beyond elite patrons. In reading accounts of many of these scientists as well as of their literary companions, one gets caught up in the excitement of discovery and the love of exploring. Indeed, science and geographical exploration were often intertwined when explorers of unknown parts of the world came back to the Royal Society (whose members were often their sponsors) to lecture on their trips. The childlike sense of wonder is unmistakable. The poet/critic/theologian Samuel Coleridge offers many examples in his arresting prose:

> The first man of science was he who looked into a thing, not to learn whether it furnished him with food, or shelter, or weapons, or tools, armaments, or playwiths but who sought to know it for the gratification of knowing.[18]

In 1802, Coleridge attended Davy's extensive lecture series on chemistry at the Royal Institute and justified his perfect attendance on literary grounds, remarking that he "attended Davy's lectures to renew my stock of metaphors."[19] Davy was the ideal scientist for this period because his lectures on major scientific advances were utterly captivating and immensely popular to all who attended. He fostered a vibrant and remarkably diverse community fascinated with knowing more, a community that extended, through collaborations and competitions, to France, Germany, and other parts of Europe and even to the recently created United States.

Interdisciplinary flowerings have been described at other times in history. In the West, during the Golden Age of Greece from 500 BCE to 300 BCE, Plato, Socrates, and Aristotle proposed ideas and models that are still discussed today. The "Anadalusian Enlightenment" or "El Andalus" occurred between roughly 1000 CE and 1250 CE.[20] Scientists, mathematicians, and humanists from diverse backgrounds came together in medieval Spain in a burst of creativity and scholarship. Baghdad has been called the center of a Golden Age of Islam starting at around 750 CE. In China, the Song Dynasty (960–1279 CE) is often characterized as period of remarkable intellectual freedom, creativity and innovation. A golden age has been described in central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) from roughly 800–1100 CE, with major advances across the sciences and the humanities.[21] There are surely hundreds more cases in which communities became inspired by a few charismatic lifelong "wonderers" and were protected by governments that tolerated and even encouraged new lines of thought and creative work. The European Enlightenment may have had a huge impact on history up to the present,[22] but vibrant communities of wonder seem to sprout up for brief intervals throughout the sweep of history.

My elementary school years coincided with an exuberance for science in my community. This occurred largely because of the successful launching of Sputnik 1 by the Soviet Union on October 4 1957. The ability of our bitter cold-war enemy to put something in orbit "over our heads!" aroused strong reactions in the United States, much of which centered around our failings in science education and our neglect of the next generation of scientists.[23] The United States responded with an avalanche of resources, funds, and new ways of teaching science. It is unfortunate that this surge of support for science education was fueled in part by fear and nationalism, but, within my circle of friends, the perceived Soviet threat simply added to the excitement.

From the first grade on, I witnessed a rise of science demonstrations and projects in school and a rapid growth of science projects in our homes. Virtually all my friends owned at least one chemistry kit, many of which were surprisingly poisonous and dangerous. I'm pretty sure one of my kits had arsenic and bits of radium and that my friends had other more pyrotechnic components. In addition, a never-ending stream of science stuff arrived at our house. These packages came from grandparents, aunts, and friends of the family. Rocket kits showed up at our door, not just of the vinegar and baking soda type but of much more powerful chemical mixtures. I was the proud recipient of electronic circuit kits, crystal radio assemblies, Erector sets, and The Visible Man, which was a transparent plastic human shell in which you could place all the bodily organs like a 3D jigsaw puzzle. The Man was followed later by The Visible Woman with a pop-out pregnancy unit. I received in the mail every month little blue boxes called Things of Science, which provided the materials and instructions needed to perform experiments in biology, chemistry, and physics.

Ominous portrayals emerged of how badly the Russians were beating us. The education scholar Jeffrey Herold described a CBS broadcast that reported on a "typical" Russian teenager suspiciously named Ivan who seemed to excel in all areas of study and extracurricular activities.[24] The show then interviewed teenagers from Tennessee about their thoughts on the report. The Tennesseans did not think much of Ivan, declaring him to be a bore who studied too much and probably wasn't very good at getting along with others. Herold saw it as a devastating portrayal of Americans. They cared about learning and achievement while we only cared about peers and popularity.

In my school, I frequently heard reports of how far ahead our Russian peers were in math and science and how much harder they worked. I distinctly remember statements that the best students were studying "calculus" before high school. I didn't really know what calculus was except that I knew it was not even studied in most US high schools. This glaring disparity was certainly repeated beyond my neighborhood. *The Sputnik Moment*, a documentary film by David Hoffman, details how, nationwide, we were told that Russian children went to school six days a week and were in school for a month longer each year. They averaged four hours of homework a night while we averaged thirty minutes. We were repeatedly told that Russian children had much more math, science, and engineering instruction than we did. Somehow, none of these reports about Russian achievements were daunting or intimidating to my peer group. We regarded them as challenges to be met and were confident that we could meet those challenges and have much more fun than the Russians in the process. We also somehow sensed that the Russians were probably exaggerating (see figure 1.1) and that we shouldn't worry if we weren't immediately doing calculus in the fifth grade. In retrospect, our confidence may not have been completely foolish. After all, in 1961, President Kennedy announced to the country that we were going to land on the moon, and eight years later we did just that.

A massive infusion of US funds into science and science education ensued. Everyone seemed to celebrate all that was science, math, and engineering. If you were five and had a lot of wonder, it was a pretty great time. In retrospect, I appreciate how the science-loving frenzy and the ballooning resources were uneven. Despite some attempts to include girls, science was heavily gender biased and almost completely ignored minority groups. Nor was it interdisciplinary. No one attempted creative fusions with the humanities. The only interest in fusion was thermonuclear. Yet, given my small corner of the world and my early experiences, that explosion of interest in science helped fuel my own little age of wonder. Flourishing pockets of wonder are surely happening in various places around the world today as well, but they aren't nearly as pervasive as they might be. They should be seen as the norm, not as rare, exotic, and fragile flowers.

In addition to the developmental decline in wonder, has there also been a drop in adult scientific wonder since the middle of the past century? Fond

Figure 1.1
A third-grade student in Moscow in the early 1960s, seeming to confidently answer a question in an attentive classroom. This is just one example of an avalanche of similar depictions that circulated in the United States after the embarrassing launch of Sputnik. Despite being told that Russian children were far ahead of the United States in math and science in terms of curriculum and work ethic, rather than being discouraged by such comparisons, many children of my generation were inspired by such possibilities as the United States greatly ramped up support for science education.

reminiscences of "the good old days" are all too often reflections of a recall bias rather than careful historical analyses.[25] Riding a wave of youthful science nostalgia can easily cause a mistaken generalization that the culture as a whole was more positively engaged with science. For those reasons, I must be cautious about drawing such a conclusion. That said, the world of science and engineering in the 1950s and 1960s is very different from today. As we consider developmental changes, it will be useful to occasionally consider how science and technology and the surrounding culture have changed as well over the past seventy years. In several cases ranging from educational practices to the nature of science and technology, there are reasons to worry. There is certainly at present ample discussion of the importance of training our youth for science, technology, engineering, and mathematics (STEM) careers, but that emphasis is not the same as nurturing a self-sustaining interest in science in young children and continuing to have that intrinsic interest as adults.

Wonder has social consequences. It can be rebellious and disruptive. Acts of wondering, especially asking why and how, have been called moral vices. Augustine and many others condemned the seeking of knowledge and understanding as abominations arising from lust, pride, and vanity.[26] Such sentiments often lead back to Adam and Eve's original sin at the tree of knowledge and the inference that it is wrong to want to know why and how. Engaging in such actions could lead to blasphemous challenges of religious doctrine, to atheism, and to acquiring forms of forbidden knowledge.[27] Active, free wonderers can be seen as heretics who challenge the status quo. Yet, while many have characterized questioners and knowledge seekers as prideful and vain, psychological research shows just the opposite. The more you know, the more you realize the limits of your knowledge.[28] As Socrates observed many centuries earlier, knowledge enhances humility, not arrogance. Wondering is extraordinary in that it is an act both of humility and of intellectual independence. We all have a right to wonder about why things are the way they are and how they might be different. To preserve and nourish the child's sense of wonder intact is to preserve everyone's right to question anything and to explore alternative possibilities. More mission-oriented episodes of wondering can certainly be less noble, such as wondering about better weapons during the cold war or about the possibility of improving humans through breeding during the eugenics movement in the United States,[29] but to suppress or prohibit those acts is surely not the way to devalue them. In its pure form, Rachel Carson saw wonder and humility as intertwined "wholesome emotions" that "cannot exist with a lust for destruction."[30] When wondering is not task driven and is uncensored and intrinsically motivated, we may inevitably come to appreciate the moral pitfalls laying along some paths of conjecture.

Beyond the Natural Sciences

This book focuses mostly on the rise and fall of wonder in the natural sciences and engineering. Why not all other fields of inquiry? Children and adults can clearly experience knowledge hungers and exploratory drives for the social sciences and the humanities. A child can ask why friends fight more with each other when they are both tired, why popular toys cost so much, why children's books have so many talking animals, or why most songs go up and down in notes instead of continuously up or down. These, not instilled or encultured. It is a universal, native quest for understanding fueled by an exploratory drive that provides important adaptive benefits to a growing human. Wonder is revealed and supported by the extraordinary ways in which infants and young children grasp and expand on their causal understandings of what is around them. It is also deeply social, flourishing in conversations, pedagogy, and interdependent knowledge networks.

A closer look at the goals of wonder and the resulting internal mental representations reveals a particular mode of thought as central: the mechanistic mind, that is, a deep interest in how things work. Children appreciate early on the special powers of mechanistic explanations and seek them out, share them, and deploy them with great agility. They seek out mechanistic details but then use those details to create abstract causal generalizations about different classes of phenomena. Those more general causal sketches help them understand new phenomena even as they may forget the lower level details that built those sketches.

While wonder may arise spontaneously in all young children, it needs to be nourished and supported by others to flower. This can occur early on primarily through appropriate interactions with others. However, it can also be discouraged and smothered, and this happens all too often. It happens among even the most well-intentioned adults if they misconstrue how children naturally understand the world and how their understanding changes with development. It can occur when adults and the culture at large create systems and processes that undermine the motivations that support wonder-driven activities.

When wonder is stifled and demotivated, it can lead to cognitive decay that makes us all more susceptible to misleading cognitive biases, misinformation, and the blind following of consensus. Ultimately, a life without wonder can lead to disengagement, disillusionment, and even distrust of science. When this happens, we lose touch with the ability to engage in meaningful discourse about science when it matters most.

Fortunately, even when everything has worked against wonder, we can also reawaken it in ourselves and in our communities. This isn't just blind Pollyannaish optimism. It calls for a program of small- and large-scale activities, mostly low-cost and easily implementable. These activities can rekindle the flame inside of us and allow us all to share the glowing warmth of wonder. We therefore start with the youngest humans.

2 Early Exploration and Discovery

Young children don't always get things right. They can develop ideas about nature and technology that most adults see as clearly wrong. But, just as even the most advanced scientists sometimes also get things wrong, it is how they are mistaken that matters. What does their error tell us about how they think and how they build their knowledge and understanding? In many cases, impressive inferential machinery is revealed. One, summer when our son Derek was almost four, he asked a surprising question: "Do trees have hearts?" Rather than simply say they didn't, I asked him why he asked. A flood of statements ensued: "Because people have hearts and yesterday you said Daisy (our dog) needed her heart medicine. So people and dogs have hearts. And when I asked about Daisy, you said all animals need hearts 'cause they pump blood all over and that's how food gets to all parts of their body. . . . so trees must have hearts too." When I asked why trees had to have hearts, he said, "They were alive 'cause they grew bigger, made new leaves every year and made seeds for more trees and even fixed themselves when they got hurt. So . . . they must have blood and a heart to move all their food around to do those things; maybe their blood was like maple syrup." (Some neighbors had maple trees with collection pails.) At this point, I finally said trees didn't really have hearts, and my son immediately demanded to know how they pushed all their blood around. I madly tried thinking about osmotic pressure, capillary action, and photosynthesis in leaves and realized I had nothing to offer that made any sense. So . . . I punted with the usual: "It's complicated."

A great deal of thinking and reasoning were going on here, much of which unfolds in the next several chapters. To anticipate, young children are infused with spontaneous curiosity and a drive to find certain kinds of answers. They constantly mention causal relations and make inferences that transcend what it immediately present. The developmental psychologist Jerome Bruner famously described the phenomenon as follows: "Being able to 'go beyond the information' given to 'figure things out' is one of the few untarnishable joys of life." In Derek's query, we see the opportunistic use of information that I had provided earlier in the same conversation. This ended up creating errors, but errors that revealed insight as well. How does all this cognitive machinery get off the ground? It all starts in infancy.

Well before they are able to produce or understand language, human infants are curious about how and why things happen. They rapidly develop intuitions about the causal patterns around them. Because of these early abilities, preverbal infants are sometimes described as "scientists in the crib," but such accounts quickly run into arguments about what it means to be a scientist. In many senses of the word, infants are not scientists. They do not propose formal hypotheses and test them in carefully controlled ways, and they do not participate in arguments concerning their views. Yet they do have interpretative and predictive skills similar to those used at all ages to make sense of complex systems. Infants also explore objects in ways suggestive of "hypotheses." These preverbal exploratory activities are early signs of their drive to learn. Both in terms of tracking causal patterns in the world and in terms of using strategies for learning more about the world, infants can be surprisingly proficient.

The past few decades of research on infants' and children's minds consists of many thousands of studies covering a huge range of topics.[1] A one-line summary of much of that research is a string of discoveries showing far more cognitive ability in infants and young children than was previously believed. These early cognitive capacities provide critical components for a developing sense of wonder. To see how this occurs, we need to clarify what aspects of thought are needed to grow the earliest traces of wonder into fully functioning engines of imagination and discovery.

Four components greatly facilitate an emerging sense of wonder in the individual child: (1) a rapid and automatic way of gathering data about the world, (2) an appreciation of the distinctive role of causal relations, (3) an ability to conceive of domains of things that cohere because they share common causal patterns that form stable clusters, and (4) a sense of how such domains might interact in systematic and predictable ways with other domains. Collectively, these skills support a cycle of activity that enables children to puzzle over a problem, to formulate conjectures or hypotheses about possible alternatives, and to consider counterfactuals before updating their puzzling. These four abilities and the cycle undergird wonder and allow it to be an engine of conceptual change. They do not exhaust aspects of cognition that support wonder. Others include executive functioning, the ability to simultaneously represent several alternative models or theories, logical and analogical reasoning, and an ability to weigh probabilities, but I see these four as the central ones that arise in infancy.

This discussion of cognitive development of a child as an independent learner will then enable us to consider in chapter 3 how wonder goes beyond the individual mind to expand greatly in power by drawing on what others know. Finally, the most powerful and relevant use of wonder for science involves a special appreciation for what we describe in chapter 4 as the mechanistic mode of understanding.

Data Aggregators

To wonder about the world requires at least a crude sense of stable patterns in that world. These patterns recur often enough to be noticed among the noise and confusion that also confront the child. Science relies on the tabulation of statistical patterns in time and space. When certain events co-occur repeatedly, such as lightning and thunder, we notice and remember that relationship. Scientists track correlations, frequencies, and contingencies and use those patterns to make predictions and support explanations. Every adult automatically engages in this tracking of correlations and contingencies at an implicit level all the time.[2] Infants are also impressive statistical learners. They notice and remember correlations and contingencies long before they have any way of explicitly talking about them.

Infants' abilities to track patterns were demonstrated in a series of landmark studies that first appeared in 1996.[3] The studies focused on how infants identified artificial spoken words embedded in much larger strings of spoken syllables. When infants hear a string of syllables, such as po-ta-to, repeatedly occurring, do they start to see that string as somehow special and cohering as a unit, namely *potato?* They do so easily. In fact, infants under six months can learn new artificial words in under two minutes. (They are artificial to make sure infants don't already have experience with them as words.) In the studies, infants listen to much longer strings of syllables in which certain artificial words, such as *bidaku*, repeatedly occur amid other nonrepeating random strings of syllables. No other cues to repeating triplets are present such as intonation, special stress, or pauses. Based solely on repeated co-occurrences, infants reliably came to expect such sequences to occur again in the future in comparison to other completely novel three-syllable sequences for which they showed no such expectations. Because novel word learning can happen when the co-occurrence patterns are highly likely but not perfect, we can think of the infants as mentally tabulating things like correlations and probabilities.

This kind of early learning has been called *statistical learning*, and young infants display such an ability not just for repeating speech sounds but also for musical tones and for repeating visual patterns.[4] Infants and adults learn these statistical regularities without any awareness that the learning is occurring. Statistical learning can occur automatically without effort or goals to learn.[5] It may therefore also be involved in creating implicit attitudes,[6] those sets of impressions we develop toward others and that have been linked to racism, sexism, and other antigroup impressions.

The ease with which young infants do automatically learn statistical patterns cannot explain many aspects of learning,[7] but it is an important part of a cognitive system capable of wonder. We need to constantly update our mental database of the recurring patterns that we encounter. To wonder why cats crouch before they leap, you have to first notice and remember that regularity. But humans go far beyond noting co-occurrence patterns. We overlay those patterns with causal interpretations that provide new meanings to events and that impel us to learn more about them.

The Causal Connection

A fundamental skill in understanding the world involves detecting causation as opposed to mere correlation. This contrast is stressed even at the university level as faculty frequently caution their students not to leap from strong correlations to conclusions about causal relations. For example, the positive correlation between years of education and health does not lead to the simple conclusion that more education causes better health. There are likely causal links between the two measures but they run in both directions and often involve interactions with other factors such as income.[8] A more obviously silly faux causal link between two variables is

While researchers still actively debate when the first causal intuitions emerge in infancy and how they are represented in the mind, they all agree that, by twelve months, infants are especially attentive to causal relations. Their tendency to notice and remember causal relations also forms the basis for their ability to notice those clusters of causal relations that distinguish different domains of things.

Demarcating Domains

Causal relations often come in characteristic groups or clusters. For example, in thinking about two people, I might notice that, in contrast to a pair of billiard balls, they often causally act on each other at a distance. A remark to a person several feet away can cause that person to move quickly backward. Cause-and-effect relations for people have longer time lags than for balls. You do not move instantaneously after I speak, unlike cases in which one ball launches another. There is a noticeable lag. People move on their own without needing any external force. Simple balls do not spontaneously move. Self-generated motion conveys the strong impression that something inside the mover is causing the movement. People can move in irregular ways, darting this way and that. Balls move in smooth predictable paths unless something else intervenes. People interact contingently; balls do not. There is a back-and-forth rhythm to many human social interactions whether they be conversations, silent greetings, or hot pursuit. Taken together, several interacting causal relations distinguish the motions of people from those of simple solids. And of course, these patterns extend far beyond humans to dogs and cats and all sorts of other less familiar creatures.

By twelve months, infants are well aware of these two contrasting pairs of causal regularities related to motion.[14] They may have not yet integrated all the relations that toddlers notice, but they notice a complex set of interactions that give them a sense of two starkly contrasting realms, one concerning agents and one concerning simple solid objects. Infants' awareness of these two realms, or domains, is sometimes described as the earliest forms of an intuitive psychology and an intuitive physical mechanics. But an intuitive psychology, no matter how primitive, ought to include some notion of internal mental states. For that reason, a great deal of research has focused on whether infants also make inferences about goals.

Reaching is an action that automatically suggests goals to adult observers, but not just any goal comes to mind. When you observe someone reaching for an object, you normally assume they have the goal of contacting that object and probably retrieving or manipulating it. You don't assume they have the goal of moving their hand to that specific location in space without any interest in the object itself. Do infants have similar assumptions?

An influential line of work initiated by the psychologist Amanda Woodward in 1998 has examined inferences made by infants when they observe a hand reaching for a particular object. For example, a hand might reach for a teddy bear on a pedestal at a specific location A.[15] This reaching happens repeatedly until the infants no longer find it interesting. The infants are then shown one of two displays: (1) The hand moves to the same location A but now is moving toward a different object such as a ball, or (2) The hand moved to a new location B but toward the same teddy bear as before. In this pair of situations, infants look longer at reaches for the ball in the same location than for the teddy bear in a new location. Looking longer is interpreted as evidence that the infants' expectations are violated, or in more familiar terms, they are surprised. (They do not, however, usually show facial expressions of surprise that we so commonly see in older children and adults.)

Now consider the same set of events with the teddy bear and the ball, but where, instead of a hand, the initial repeated action is executed by the movements of a clearly inanimate wooden stick. As adults, when we watch a stick repeatedly move toward the teddy bear in location A, we develop an expectation that it will again go to location A when the ball has been moved there and the teddy bear is at location B. We assume that the stick just mechanically and deterministically follows the same path as always, and we definitely do not attribute any goals to the stick. Infants as young as five months have similar expectations. They look longer when they observe the stick "reach" for the old object in the new location. They too see the stick as destined to move in precisely the same physical path again and again. The hand's movements are seen as being controlled by an actor with the goal of obtaining the object regardless of its location.

Infants quickly code objects as either goal-directed or not by using several kinds of cues. The object might look like a hand or contain a face-like pattern. It might respond contingently to the actions of another object some distance away.[16] It might move in an obviously self-propelled manner. Even a simple triangle can acquire goal directedness if contingent changes of movements create an impression of the triangle "chasing" another geometric figure.[17]

As adults, when we see self-propelled objects with goals, we also assume that the causes behind all these movements come from within the objects themselves. We see humans and animals as acting in ways that arise from events happening inside them and do not make such inferences for simple inanimate things. Our research group initiated a series of studies testing this idea with fourteen-month-old infants. The infants watched videos in which animated cats either swayed back and forth or jumped up and down.[18] The cats were unusual in that their insides were visible through a kind of semitransparent skin and fur, a manipulation that was surprisingly unproblematic for our infant observers. Each cat was depicted with hats and stomachs of the same color, red or blue. When shown new videos in which the stomachs and hats of each cat differed in colors, infants expected cats with the same colored stomachs to move the same way and ignored whether or not the hat was the same color across movements. Hat color was seen as irrelevant to a cat's manner of motion while stomach color was seen as critical. Using different measures and different versions of agents and inanimate counterparts with revealed insides, other groups have found the same expectations about insides in infants as young as ten months.[19]

This preference for insides in understanding animate creatures may be a precursor sign of a more general bias to infer that surface properties and behaviors of certain kinds of things (e.g., animals) arise causally from essential inner features. An early version of such an *essentialist bias* could provide a useful strategy for guiding exploration of a thing given its general category. If something seems to be an animal, assume that the most important things to know about it are inside.

Infants know more than the contrast between an early physics of simple inanimate objects and a psychology of social things, although perhaps in fragmentary forms. Two other examples from infants' understandings of plants and liquids make the point:

Infants apparently view plants as both important and potentially dangerous.[20] They are more reluctant to touch novel plants than novel control objects that are superficially shaped and colored like plants but clearly appear as human made. This reluctance is equally strong for plants with delicate soft leaves and plants with sharp thorns, suggesting a deep-seated sense that plants of all kinds might mean trouble (as irritants or poisons). At the same time, infants carefully observe how other humans behave around plants and take special notice of any plants that adults bring to their mouths in comparison to the artifacts they bring to their mouths. Plants are things to carefully monitor in terms of how others interact with them. They could cause great harm or they could be tasty food. Not until the preschool years and later, however, do children appreciate important commonalities between plants and animals.

Infants have distinct and specific expectations about the behaviors of liquids as opposed to solids. Thus, they expect liquids in a glass to stay horizontal when the glass is tipped but expect solids to tip with the glass. They know that liquids can pass through grids while solids cannot. They also easily extend their inferences about liquids to loose granular substances like sand.[21] They need to appreciate these contrasting causal clusters if they are to later wonder why cold transforms water from a liquid into a solid. Such a transformation must seem especially miraculous when first encountered if the observer appreciates all the causal patterns that distinguish solids and liquids.

Interactions between Domains

Intuitive expectations about causal clusters associated with broad domains such as goal-directed agents and physical objects allow us to think about how two or more domains might causally interact. How do interactions between goal-directed agents and physical objects differ from those between two physical objects? A key contrast concerns the ability of goal-directed agents to create order out of randomness. When you witness a transformation of disorder into order, you immediately infer that an agent has been involved.

These linkages of order with goal-directed agents motivated the "argument from design." Prior to Darwin, an invisible deity was often inferred as necessarily behind much of the order present in the biological world. Everyone agreed that humans could not have created most of the systematic structure that was so apparent in plants and animals, much of which clearly served obvious functions. In 1802, the Reverend William Paley argued that some kind of powerful deity must have been responsible for the highly ingeniously designed properties of the eye.[22] For Paley, the eye virtually shouted that it was created by a goal-directed agent in much the same manner as a clock.

The degree of order does not have to be nearly as complex as an eye to elicit a sense of agent involvement. Hikers routinely encounter simple clusters of rocks on beaches and mountain trails indicating that an agent must have been there. An enormous range of configurations can irresistibly suggest order. For example, four rocks strongly imply placement by a human agent if they form a straight line; form a neat square; are stacked on top of each other; or are ordered according to size, darkness, or smoothness. These examples hardly exhaust possible cues, which in turn proliferate when larger numbers of rocks are involved. This ability to detect order applies to many configurations that we have never seen or even imagined before.

Figure 2.2 shows the ground in the wild interior of Iceland. It is immediately obvious that aspects of this terrain were created by humans and did not occur naturally. The stack of rocks in the foreground and the smoothly

Figure 2.2
This scene, composed entirely of naturally occurring objects, nonetheless immediately indicates a kind of order that we would only attribute to goal-directed agents. It "insists" that an intentional agent must have created the array and that it couldn't have possibly arisen though random processes.

encounter a device that apparently violates one of its principles? How does witnessing a violation influence an infant's behavior? In terms of wonder, such experiences may greatly accelerate the development of wonder through engaging in the PHED cycle. Using the cycle involves posing *P*uzzles, inspiring conjectures and *H*ypotheses, motivating *E*xploration, and affording *D*iscoveries, which can then cycle back to help pose new puzzles. This tightly interconnected combination of cognitive activities, or PHED cycle, continuously creates more and more elaborated versions of wonder while also "feeding" the hunger for new insights.

Puzzlement is one sign of responding to violations and anomalies. Psychologists Aimee Stahl and Lisa Feigenson asked how infants' explorations of objects might vary when those objects either behaved in ways that violated core physics or did not. Violations included passing through another physical object or seeming to go behind one screen and emerge from behind another without traversing the space in between. When eleven-month-olds witness such violations, they explored the deviant objects more fully and learned more from those explorations.[27] Their curiosity was triggered, and their subsequent investigations suggested that they wanted to know why the object was behaving oddly. In such cases, a combination of special cognitive states seems to occur that were described as surprise, enhanced interest, curiosity, and some version of answer seeking or exploration. Presenting children with such core anomalies can result in their being fully engrossed in the PHED cycle. By better remembering new information about objects that violated core knowledge, the infants apparently assumed it was important to specifically focus on the peculiar objects' properties so as to learn what might explain their bizarre behaviors. Similarly, when given a choice between exploring the core-knowledge-violating object and another control object, infants strongly preferred to examine the one that had just behaved oddly.

More subtly, preschoolers show increased exploration when "evidence is confounded." When presented with a jack-in-the-box toy that prior evidence suggests is triggered by either one of two handles (confounded), they will explore the object more to determine the real cause.[28] No one has to motivate the child to explore more; the child does so because of an intrinsic interest. Children recognize a gap in their knowledge, or an uncertainty about which of two possible handles made the toy pop up. Then, on their own, they seek to find out which handle is the causally relevant one.

Recognizing gaps in one's knowledge can be a challenge for even the most sophisticated scientists, but at least in some simplified tasks, young children not only recognize the gap, they seek to remedy it. Exactly how they construe the gap remains unclear. Is it seen as a missing bit of knowing how to operate the toy or as a missing bit of understanding how the toy works, or both? Such contrasts matter greatly and may ultimately be at the heart of the kind of wonder that fosters engagement with science.

Infants and young children therefore show curiosity and exploration for at least two reasons. Violations of core theories trigger surprise and exploration in infants, and, by the early preschool years, ambiguity about causes prompts exploration to determine which factor is the true cause. But these two processes, impressive as they are, do not fully characterize why children and adults engage in inquiry about their natural and engineered worlds. Consider why you might choose to read a new article in the science section of the *New York Times*. Sometimes the title may indeed refer to a provocative anomaly: "The Loudest Bird has a Song Like a Pile Driver." Other times the title may examine two possible causal patterns: "Meat's Bad for You! No, It's Not! How Experts See Different Things in the Data." But we often are simply told a fact that seems worth reading more about, such as "This Fungus Mutates. That's Good News if You Like Cheese," or "In the Sea, Not All Plastic Lasts Forever," or "The Twitch That Helps Your Intestines Grow." We are presented with the opportunity to learn more about something not because it is especially surprising or because we have clear alternatives in mind, but rather because we see the promise of an interesting story that will enable us to understand some corner of the world more clearly.

Infants and young children may also pursue information for other reasons than explaining anomalies or choosing among two clear alternatives. They may simply want to gain a better sense of what is going on around them so that they can act on their world more effectively in terms of navigating spaces, fixing objects, and predicting outcomes. We may seek out information to fill out the picture, complete the story, or finish a project. We care about closure because it provides an opportunity to pause and encode in memory what happened.

Consider how some people, including some young children, enjoy doing jigsaw puzzles for hours. There are no big surprises. (Unless the last piece has been hidden by a sly sibling.) The players know exactly what the end result will look like and are rarely startled midway. But there can still be great satisfaction upon completion. When listening to an interesting story, we can be deeply disappointed if we don't get to hear the ending. When exploring a new place such as a house or a park, we often want to get a clear sense of the overall layout and can be frustrated if we don't know how different locations fit together. Infants, like all of us, strive to achieve closure. They have a need to identify *all* the toys that are in a box, or explore *every* room of a new space. They have similar needs for closure in their causal models of how things happen. This constellation of needs for closure often helps drive wonder, especially when there is a need to close an explanatory gap.

Causal Elaboration and Integration beyond Infancy

Causal understanding grows greatly between two and five years of age. The most consistent overall developmental change during this period is increasing integration of all the different streams of causal information.[29] Children become more adept at inferring how causes are stronger when causes and effects co-occur more frequently. Infants also expand their ability to learn hidden causal relations by observing covariation patterns, namely how often one event (such as a solid object dropping down toward water) is followed by another (such as a splash). They also can learn a great deal by manipulating parts of a device. For example, they can learn whether the underlying causal process is a simple linear chain of causes and effects or a branching structure where one cause has multiple effects.[30] If infants learn that turning the crank several times on a jack-in-the-box is always followed by both a clown popping up and by the playing of music, they are likely to infer that turning the crank is an initial cause that branches into two different effects.

Preschoolers begin to entertain counterfactuals in their attempts to figure out causal relations. Thus, the infant learning about the jack-in-the-box might also realize that there could be a box where the crank only causes the clown to pop up or a different one where the crank only causes the tune. Counterfactual thought is traditionally measured by the comprehension and use of such phrases as "If x didn't happen, then y wouldn't have happened either"—for example, "If the contractor hadn't used inferior materials, the bridge wouldn't have collapsed." Young children have difficulties reasoning about such sentences but they fare better when observing visual animations. To demonstrate this effect, several labs, including ours, worked together on a project showing young children sets of brief videos.[31] Children observed computer animations in which balls moved toward soccer-like goals either in straight lines or by bouncing off brick-like walls. By at least age five, they mentally simulated different scenarios that didn't happen so as to better explain what actually did happen. They were reasoning counterfactually without having to utter a word. A convergence of recent studies shows that at least by age four, children spontaneously engage in these forms of conjectures or informal hypotheses that are so central to developing more sophisticated forms of wonder.[32]

Before they enter formal schooling, children are able to quickly deploy general causal reasoning strategies while also incorporating the peculiarities of each domain. They realize that cause-effect time lags are usually longer for psychological events than biological ones. People take longer to laugh when told a joke than a window takes to break when hit by a stone. Their "causal calculus" has become both more powerful as a general skill set and more sensitive to the marked contrasts in causal patterns that occur between broad domains, domains that often resemble academic disciplines, such as psychology, physics, biology, and economics. Wonder often is the major force behind the growth of understanding and discernment in an ever-expanding appreciation of domains and demarcation of smaller areas within those broad domains, such as biology and its different realms of animals, plants, and microbes and their many further subdivisions.

Developing Biological Thought in Preschool and Later Years

Throughout preschool, children elaborate on their early models of the world as their causal reasoning becomes more intricate and far-reaching. They are able to discern new domains that cohere because of new insights into underlying causal patterns linking together entities and processes in each domain. Biological thought nicely illustrates these kinds of conceptual growth. We briefly consider here the extensive body of research on biological thought as an example of how interpretations of the world can grow between preschool and the early school years. This growth also illustrates the potential for wonder to continue on the same trajectory for a lifetime if it is embraced and supported.

A central question in early intuitive biology concerns how children come to appreciate that both plants and animals are part of a larger category of