WHY

What Makes Us Curious

MARIO LIVIO

author of BRILLIANT BLUNDERS

Contents

To my mother

Preface

I HAVE ALWAYS BEEN A very curious person. In addition to my professional interests as an astrophysicist in deciphering the cosmos and various phenomena within it, I have maintained a passion for the visual arts. I have absolutely no artistic talent, but I have amassed a large collection of art books. I am also a science advisor to the Baltimore Symphony Orchestra (yes, there is such a thing), and I have participated in a few of its concerts as a presenter of the links between science and music. Perhaps most exciting from my perspective has been my participation in the creation of the "Hubble Cantata," a contemporary classical music piece by composer Paola Prestini, accompanied by film and virtual reality, all inspired by images taken with the Hubble Space Telescope. In addition, in a regular blog posted on the *Huffington Post*, I tend to informally muse about topics in science and art and the intricate connections between them.

Not surprisingly, therefore, already a long time ago I became intrigued by the questions *What is it that triggers curiosity?* and *What are the underlying mechanisms of curiosity and exploration?* Since this was not my area of expertise, I had to engage in an enormous amount of research, consult with numerous psychologists and neuroscientists, discuss the topic with many scholars from a variety of disciplines, and interview a large number of people whom I believed to be exceptionally curious.

As a result, I am deeply indebted to scores of individuals without whom I could not have completed this project. While it would be impractical to attempt to thank them all here, I would like to at least acknowledge a group of people who have both profoundly inspired and greatly informed my writing. I am indebted to Paolo Galluzzi for an illuminating conversation on Leonardo da Vinci and to Jonathan Pevsner for helpful advice on Leonardo and for allowing me to use his vast collection of books and articles on Leonardo. Agata Rutkowska has been a wonderful guide for finding specific Leonardo drawings in the Royal Collection Trust. The Milton S. Eisenhower Library at Johns Hopkins University provided me with hundreds of books on a wide range of relevant disciplines. Jeremy Nathans, Doron Lurie, Garik Israelian, and Ellen-Thérèse Lamm introduced me to people who gave crucial interviews. I am grateful to Joan Feynman, David and Judith Goodstein, and Virginia Trimble for valuable, firsthand information about Richard Feynman.

Jacqueline Gottlieb, Laura Schulz, Elizabeth Bonawitz, Marieke Jepma, Jordan Litman, Paul Silvia, Celeste Kidd, Adrien Baranes, and Elizabeth Spelke provided me with invaluable information, sometimes even before publication, about their research projects in a variety of areas of psychology and neuroscience, all aimed at a better understanding of the nature of curiosity. Any mistakes the book might contain about the interpretation of their results are mine alone. Jonna Kuntsi and Michael Milham clarified for me concepts and potential connections between curiosity and ADHD. Kathryn Asbury discussed with me the implications of various studies involving twins for the nature of curiosity. Suzana Herculano-Houzel explained to me in detail her groundbreaking studies of the constituents of the brain in general and their significance and ramifications for the unique properties of the human brain in particular. Noam Saadon-Grossman helped me navigate the anatomy of the brain. I wish to express my gratitude to Freeman Dyson, Story Musgrave, Noam Chomsky, Marilyn vos Savant, Vik Muniz, Martin Rees, Brian May, Fabiola Gianotti, and Jack Horner for giving me fabulously interesting and insightful interviews about their own personal curiosity.

Finally, I thank my wonderful agent, Susan Rabiner, for her tireless encouragement and advice. I am grateful to my editor, Bob Bender, for his careful reading of the manuscript and his perceptive and thoughtful comments. General manager Johanna Li, designer Paul Dippolito, copy editor Phil Metcalf, and the entire team at Simon & Schuster again demonstrated their dedication and professionalism in producing this book.

Needless to say, without the patience and continuous support of my wife, Sofie, this book would never have seen the light of day.

ONE

Curious

INDEPENDENT OF THEIR LENGTH, SOME stories can leave lasting impressions. "The Story of an Hour," a very short tale by the nineteenth-century author Kate Chopin, opens with a rather startling sentence: "Knowing that Mrs. Mallard was afflicted with a heart trouble, great care was taken to break to her as gently as possible the news of her husband's death." Loss of life and human frailty all packed into one punchy line. We then learn that it was the husband's close friend, Richards, who brought the bad news, after having confirmed (by way of a telegram) that Brently Mallard's name was indeed leading the list of those killed in a railroad disaster.

In Chopin's plot, Mrs. Mallard's immediate reaction is a natural one. Upon hearing the sad message from her sister Josephine, she starts weeping straightaway, then retires to her room, asking to be left alone. It is there, however, that something totally unexpected happens. After sitting motionless, sobbing for a while, her gaze apparently fixed on a distant patch of blue sky, Mrs. Mallard starts whispering a surprising word to herself: "Free, free, free!" This is followed by an even more exuberant "Free! Body and soul free!"

When she finally opens the door, yielding to Josephine's worried requests, Mrs. Mallard emerges with "a feverish triumph in her eyes." She starts to calmly descend the steps, clutching to her sister's waist, while her husband's friend Richards awaits them at the bottom of the staircase. That's precisely when someone is heard opening the front door with a latchkey.

Chopin's story contains only eight more lines beyond this point. Could we perhaps stop reading here? Needless to say, even if we wanted to, we probably wouldn't, certainly not without at least knowing who was at the door. As the English essayist Charles Lamb wrote, "Not many sounds in life, and I include all urban and all rural sounds, exceed in interest a knock at the door." That is the power of a story that pulls your attention with such force that you don't even dream of overriding that pull.

The person entering the house is indeed, as you might have guessed, Brently Mallard, who, it turns out, had been so far from the scene of the train accident that he didn't even know it had happened. The vivid description of the emotional roller-coaster ride that the temperamental Mrs. Mallard has had to endure in the span of just one hour turns reading Chopin's drama into a riveting experience.

The last sentence in "The Story of an Hour" is even more unsettling than the first one: "When the doctors came they said she had died of heart disease—of joy that kills." The inner life of Mrs. Mallard remains largely a mystery to us.

Chopin's greatest gift, in my opinion, is her singular ability to generate *curiosity* with almost every single line of prose, even in passages describing situations in which apparently nothing happens. This is the type of curiosity that results from chills running up and down your spine, somewhat similar to the sensation you feel when listening to exceptional pieces of music. Those are subtle, intellectual cliffhangers that constitute a necessary device in any compelling storytelling, lesson at school, stimulating artistic oeuvre, video game, advertising campaign, or even simple conversation that delights rather than bores. Chopin's story inspires what has been dubbed *empathic* curiosity—the standpoint we adopt when we try to understand the desires, emotional experiences, and thoughts of the protagonist and when her or his actions incessantly bother us with the nagging question *Why?*

Another element that Chopin aptly uses is that of surprise. This is a sure stratagem to kindle curiosity through heightened arousal and attention. New York University neuroscientist Joseph LeDoux and his colleagues managed to trace the pathways within our brain that are responsible for the reaction to surprise or fear. When we encounter the unexpected, the brain assumes that some action may have to be taken. This results in a rapid activation of the sympathetic nervous system, with its familiar, associated manifestations: increased heart rate, perspiration, and deep breathing. At the same time, attention is diverted from other, irrelevant stimuli and is focused on the key pressing element under consideration. LeDoux was able to show that in surprise, and in particular in fear response, fast and slow pathways are concurrently activated. The fast track proceeds directly from the thalamus, which is responsible for relaying sensory signals, to the amygdala, an almond-shaped cluster of nuclei that assigns affective significance and directs the emotional response. The slow track involves a lengthy detour between the thalamus and the amygdala that passes through the cerebral cortex, the outer layer of neural tissue that plays a key role in memory and thought. This indirect route allows for a more careful, conscious evaluation of the stimulus and for a thoughtful response.

Several "types" of curiosity—that itch to find out more—exist. British Canadian psychologist Daniel Berlyne charted curiosity along two main dimensions or axes: one extending between perceptual and epistemic curiosity and the other traversing from specific to diversive curiosity. *Perceptual* curiosity is engendered by extreme outliers, by novel, ambiguous, or puzzling stimuli, and it motivates visual inspection—think, for example, of the reaction of Asian children in a remote village seeing a Caucasian for the first time. Perceptual curiosity generally diminishes with continued exposure. Opposite perceptional curiosity in Berlyne's scheme is *epistemic* curiosity, which is the veritable desire for knowledge (the "appetite for knowledge" in the words of philosopher Immanuel Kant). That curiosity has been the main driver of all basic scientific research and of philosophical inquiry, and it probably was the force that propelled all the early spiritual quests. The seventeenth-century philosopher Thomas Hobbes dubbed it "lust of the mind," adding that "by a perseverence of delight in the continual and indefatigable generation of knowledge" it exceeds "the short vehemence of any carnal pleasure" in that indulging in it only leaves you wanting more. Hobbes saw in this "desire to know *why*" (emphasis added) the characteristic distinguishing humankind from all other living creatures. Indeed, as we shall see in chapter 7, it has been the unique ability to ask "Why?" that has brought our species to where we are today. Epistemic curiosity is the curiosity Einstein alluded to when he told one of his biographers, "I have no special talents. I am only passionately curious."

To Berlyne, *specific* curiosity reflects the desire for a particular piece of information, as in attempts to solve a crossword puzzle or to remember the name of the movie you saw last week. Specific curiosity can drive investigators into examining distinct problems in order to understand them better and identify potential solutions. Finally, *diversive* curiosity refers both to the restless desire to explore and to the seeking of novel stimulation to avoid boredom. Today, this type of curiosity might manifest itself in the constant checking for new text messages or emails or in impatience while waiting for a new smartphone model. Sometimes, diversive curiosity can lead to specific curiosity, in that the novelty-seeking behavior may fuel a specific interest.

While Berlyne's distinctions among different types of curiosity have proven to be extremely fruitful in many psychological studies, they should be regarded only as suggestive until a more comprehensive understanding of the mechanisms underlying curiosity emerges. At the same time, a few other types of curiosity have been suggested, such as the empathic curiosity mentioned earlier, which do not neatly fall into Berlyne's categories. There is, for instance, the *morbid* curiosity that results in rubbernecking; it invariably impels drivers to slow down and examine accidents on the highway and prompts people to gather en masse around scenes of violent crimes and building fires. This is the type of curiosity that reputedly generated a huge number of Google hits for the gruesome video showing the beheading of British construction worker Ken Bigley in Iraq in 2004.

In addition to the potentially different kinds, there are also varying levels of intensity that one can associate with assorted genres of curiosity. Sometimes just a snippet of information would suffice to satisfy the curiosity, as in some of the cases of specific curiosity: Who was it who said, "Injustice anywhere is a threat to justice everywhere"? In other instances, curiosity can propel someone into a passionate lifelong journey, as is occasionally the case when epistemic curiosity shepherds scientific inquiry: How did life on Earth emerge and evolve? There are also clear individual differences in curiosity, in terms of the frequency of its occurrence, the intensity level, the amount of time people are prepared to devote to exploration, and in general the openness to and preference for novel experiences. For one person, an old bottle washing ashore on Amrum Island on the German North Sea coast may be just that: a disintegrating symbol of pollution. For another, such a find could trigger an opportunity for a glimpse into an earlier, fascinating world. A message in a bottle found in April 2015 proved to be from sometime between 1904 and 1906—the oldest-known message in a bottle. This was part of an experiment to study ocean currents.

Similarly, Ed Shevlin, a twenty-two-year New York City sanitation worker who collects trash five mornings a week, felt such great enthusiasm for the Gaelic language of Ireland that he enrolled in an NYU master's degree program in Irish American studies.

About two decades ago, a rare astronomical event beautifully illustrated how a few supposedly distinct types of curiosity, such as that evoked by novelty and the one representing the thirst for knowledge, can combine and feed each other to form one irresistible attraction. In March 1993, a previously unknown comet was spotted orbiting the planet Jupiter. The discoverers were veteran comet hunters, husband and wife astronomers Carolyn and Eugene Shoemaker and astronomer David Levy. Since that was the ninth periodic comet identified by this team, the object was named Shoemaker-Levy 9. A detailed analysis of the orbit suggested that the comet had probably been captured by Jupiter's gravity a few decades earlier, and during a catastrophically close approach in 1992, it broke up into pieces due to strong tidal (stretching) forces. Figure 1 presents an image taken by the Hubble Space Telescope in May 1994, showing the resulting two dozen or so fragments as they continued their course along the comet's path like a string of shining pearls.

Figure 1

Excitement in the astronomical world and beyond started to rise when computer simulations indicated that the fragments were likely to collide with Jupiter's atmosphere and to plow into it in July 1994. Such collisions are relatively rare (although one such impact on the Earth some 66 million years ago proved to be extremely unfortunate for the dinosaurs) and none had previously been directly witnessed. Astronomers all across the globe were waiting in eager anticipation. Nobody knew, however, if the effects of the impact would actually be visible from Earth or whether the fragments would simply be serenely swallowed by Jupiter's gaseous atmosphere like tiny pebbles by a large, undisturbed pond.

The first icy chunk was expected to hit on the evening of July 16, 1994, and almost every telescope on the ground and in space, including Hubble, was directed at Jupiter. The fact that dramatic astronomical phenomena can seldom be observed in real time (it takes light many years to get to Earth from numerous objects of interest, but only about half an hour from Jupiter) gave this event a “once in a lifetime” feel. Not surprisingly, therefore, a group of scientists, myself included, gathered around a computer screen as the data were about to be transmitted down from the telescope (Figure 2). The question on everybody’s mind was: Would we see anything?

Figure 2

If I had to give a title to Figure 2, I know exactly what it would be: *Curiosity!* To feel curiosity’s contagious appeal, all you need to do is examine the posture and facial expressions of the scientists involved. As soon as I saw this photo on the following day, it reminded me of an extraordinary work of art executed almost four hundred years earlier; Rembrandt’s *The Anatomy*

Lesson of Dr. Nicolaes Tulp (Figure 3). The painting and the photograph are almost identical in how they capture the emotion of impassioned curiosity. What I find especially fascinating is the fact that Rembrandt's focus is neither on the anatomy of the flayed corpse being dissected (though the muscles and tendons are quite accurately depicted), nor even on the identity of the dead man (a young coat thief named Aris Kindt, hanged in 1632), whose face is partially shaded. Rather, Rembrandt was primarily interested in accurately expressing the individual reactions of each of the medical professionals and apprentices attending the lesson. He put curiosity at center stage.

Figure 3

Curiosity's powers extend above and beyond its perceived potential contributions to usefulness or benefits. It has shown itself to be an unstoppable drive. The efforts humans have invested, for instance, in exploring and attempting to decipher the world around them, have always far exceeded those needed for mere survival. It seems that we are an endlessly curious species, some of us even compulsively so. University of Southern California neuroscientist Irving Biederman says human beings are designed to be "infovores," creatures that devour information. How else would you explain the risks people sometimes take to scratch that curiosity itch? The great Roman orator and philosopher Cicero interpreted Ulysses's sailing past the island of the Sirens as an effort to resist epistemic curiosity's lure: "It was not the sweetness of their voices, nor the novelty and diversity of their songs, but their professions of knowledge that used to attract the passing voyagers; it was the passion for learning that kept men rooted to the Sirens' rocky shores."

French philosopher Michel Foucault beautifully describes a few of curiosity's inherent characteristics: "Curiosity evokes 'care'; it evokes the care one takes of what exists and what might exist; a sharpened sense of reality, but one that is never immobilized before it; a readiness to find what surrounds us strange and odd; a certain determination to throw off familiar ways of thought and to look at the same things in a different way; a passion for seizing what is happening now and what is disappearing; a lack of respect for the traditional hierarchies of what is important and fundamental."

As we shall see, modern research suggests that curiosity may be essential for the proper development of perceptual and cognitive skills in early childhood. There is also little doubt that curiosity remains a powerful force for intellectual and creative expression later in life. Does this mean that curiosity is a straightforward product of natural selection? If it is, why do even seemingly trivial matters sometimes make us vehemently curious? Why do we occasionally strain to decipher the hisses of a conversation at the table next to us in a restaurant? Why do we find it harder not to listen to someone talking on the phone (when we hear only half of the conversation) than to listen to two people having a face-to-face exchange? Is curiosity entirely innate, or do we learn to become curious? Conversely, do adults lose their childhood curiosity? Has curiosity evolved during the 3.2 million years that separate Lucy—the transitional, nearly human creature whose bones were found in Ethiopia—from the *Homo sapiens*, modern humans? Which psychological processes and which structures within our brains are involved in being curious? Is there a theoretical model of curiosity? Do some neurodevelopmental disorders such as ADHD represent curiosity "on steroids" or curiosity spinning its gears?

Before seriously delving into the scientific research on curiosity, I decided (out of my own personal curiosity) to take a brief detour to closely examine two individuals who, in my view, represent two of the most curious minds to have ever existed. I believe that few would disagree with this characterization of Leonardo da Vinci and the physicist Richard Feynman. Leonardo's boundless interests spanned such broad swaths of art, science, and technology that he remains to this day the quintessential Renaissance man. Art historian Kenneth Clark appropriately called him "the most relentlessly curious man in history." Feynman's genius and achievements in numerous branches of physics are legendary, but he also pursued fascinations with biology, painting, safecracking, bongo playing, attractive women, and studying Mayan hieroglyphs. He became known to the general public as a member of the panel that investigated the space shuttle *Challenger* disaster and through his best-selling books, which are chock-full of personal anecdotes.

When asked to identify what he thought was the key motivator for scientific discovery, Feynman replied, "It has to do with curiosity. It has to do with wondering what makes something do something." He was echoing the sentiments of the sixteenth-century French philosopher Michel de Montaigne, who urged his readers to probe the mystery of everyday things. As we shall see in chapter 5, experiments with young children have demonstrated that their curiosity is often triggered by the desire to understand cause and effect in their immediate surroundings.

I don't expect that even a careful inspection of the personalities of Leonardo and Feynman will necessarily reveal any deep insights into the nature of curiosity. Numerous previous attempts to uncover common features in many historical figures of genius, for instance, have exposed only a perplexing diversity with respect to the backgrounds and psychological characteristics of these individuals. Take the scientific giants Isaac Newton and Charles Darwin. Newton was distinguished by his unparalleled mathematical ability, while Darwin was, by his own admission, rather weak in mathematics. Even within classes of masterminds in a given scientific discipline, there appears to be an ambiguous array of qualities. Physicist Enrico Fermi solved very difficult problems at age seventeen, while Einstein was, relatively speaking, a late bloomer. This is not to say that *all* efforts to identify a few shared characteristics are doomed to fail. In the area of prodigious creativity, for example, University of Chicago psychologist Mihaly Csikszentmihalyi has been able to unearth a few tendencies that appear to be associated with most unusually creative persons (those are briefly described at the end of Chapter 2). I therefore thought it a worthwhile exercise at least to explore whether there was anything in the fascinating personalities of Leonardo and Feynman that could provide a clue about the source of their truly insatiable curiosity. The key point for me was the fact that irrespective of whether Leonardo and Feynman had anything in common other than their curiosity, they both stood so high above their respective surroundings in terms of their spirit of inquiry that any stab at viewing things from their perspective was bound to be stimulating. I start with Leonardo, who once elegantly expressed his own passion for comprehension by saying, "Nothing can be loved or hated unless it is first understood."

By the way, in case you are curious to know whether we actually saw anything when the first fragment of Comet Shoemaker-Levy 9 hit Jupiter's atmosphere—we did! At first there was a point of light above Jupiter's edge. As the fragment penetrated the atmosphere, it produced an explosion that resulted in a mushroom cloud similar to that created by a nuclear weapon. All the fragments left visible "scars" (areas with sulfur-bearing compounds) on Jupiter's surface (Figure 4). Those smudges lasted for months until they were smeared out by streams and turbulence within Jupiter's atmosphere, and the debris diffused down to lower altitudes.

Figure 4

TWO

Curiouser

THE IMAGE WE HAVE TODAY of Leonardo da Vinci was perhaps best encapsulated by two short sentences of Giorgio Vasari, author of the celebrated *Lives of the Most Eminent Painters, Sculptors and Architects*, who was just eight years old when Leonardo died. Vasari wrote in admiration, "Besides a beauty of body never sufficiently extolled, there was an infinite grace in all his actions; and so great was his genius, and such its growth, that to whatever difficulties he turned his mind, he solved them with ease." I would have made only one small revision to this description, to read "so great were his genius and *curiosity*, and such their growth."

When he came to elaborate on those splendid attributes, Vasari emphasized Leonardo's great capacity to rapidly learn new subjects in an astonishing variety of disciplines: "In arithmetic, during the few months that he studied it, he made so much progress, that, by continually suggesting doubts and difficulties to the master who was teaching him, he would often bewilder him. He gave some little attention to music, and quickly resolved to learn to play the lyre, as one who had by nature a spirit most lofty and full of refinement: wherefore he sang divinely to that instrument, improvising upon it." In light of these effusive accolades, it may come as a surprise that more recent studies have revealed that Leonardo's notes in mathematics actually contain some embarrassing mistakes and oversights, for example in the extraction of roots. Similarly, Leonardo could not read Greek, and he read even Latin with difficulty, usually assisted by knowledgeable friends. On the face of it, these two traits, an incredible ability to acquire new knowledge coupled to bewildering gaps in basic education, appear to be in serious conflict. Two facts, however, provide at least a starting point for an explanation. First, Leonardo's early education at Vinci was rather rudimentary, and when he apprenticed in Master Andrea del Verrocchio's atelier in Florence, he trained to be an artist, not a scientist, mathematician, or engineer. Accordingly, he studied basic reading and writing, supplemented by techniques in painting, sculpting, and some practical rules of geometry and mechanics and those practices needed for metalworking. No one could have predicted that from such inauspicious beginnings Leonardo would rise to become the symbol of the Renaissance ideal of the universal man. All of his eventual, seemingly all-encompassing erudition was self-taught or gained from ceaseless experiments and observations much later in life. In fact, as a result of the void in his command of the classics, the humanistic scholars of Leonardo's time condescendingly repeated his own self-description as "a man without letters" or "not well read." Leonardo himself was quick to add, however, "Those who study the ancients and not the works of Nature are stepsons and not sons of Nature, the mother of all good authors." Defying the critics he continued, "Though I may not like them, be able to quote other authors, I shall rely on that which is much greater and more worthy—on experience, the mistress of their masters." Leonardo was without a doubt the archetypal "disciple of experience."

Vasari also provides us with a second clue that could potentially demystify the contradictory facets in Leonardo's education: "For he set himself to learn many things, and then, after having begun them, abandoned them." In other words, Leonardo did not persist in some of his studies. This, however, introduces a new puzzle: Why would Leonardo abandon topics in which he had initially shown great interest? This is an important question to which we shall return, since it may provide some insights into the workings of Leonardo's curiosity-driven mind.

To simply state that Leonardo was a curious person would be the understatement of the millennium. Suffice it to note that even a partial inventory of his library in 1503–4 contains no fewer than 116 books covering a staggering breadth of topics. Those range from anatomy, medicine, and natural history, through arithmetic, geometry, geography, and astronomy, all the way to philosophy, languages, literary works, and even religious treatises. And this was the library of a man who, by all accounts, much preferred experimentation to reading—so much so, in fact, that historian of science and Leonardo scholar Giorgio de Santillana entitled one of his lectures "Leonardo and Those He Did Not Read."

One of the most intriguing aspects of Leonardo's personality is the apparent conflict between his compassionate aesthetic sensibility and his unemotional, superhumanly sharp eye when it came to analyzing the secrets of nature. The physician and historian Paolo Giovio provided us in 1527 (only eight years after Leonardo's death) with an introduction to Leonardo's unique view of what he regarded as the inescapable links between science and art. Giovio wrote, "Leonardo da Vinci . . . added great lustre to the art of painting, denying that this could be properly carried out by those who had not attained the noble sciences and liberal arts necessary to the disciples of painting." To illustrate Leonardo's distinctive approach, Giovio describes in succession a few of the many scientific activities undertaken by the master in conjunction with painting: "The science of optics was to him of paramount importance. . . . He dissected the bodies of criminals in the medical schools . . . in order that the variations of the joints of the limbs flexed by the actions of the nerves of the vertebrae should be painted according to the laws of nature."

Giovio's report correctly conveys the important fact that in his early work Leonardo used nature as a servant of his art: he examined the natural world to make his artistic representation as accurate as possible. Later in life, however, art became the obsequious assistant of his scientific investigations: he used his singular artistic ability to depict natural phenomena and to attempt to ascertain their causes.

As early as two decades before Vasari, Giovio too commented on Leonardo's apparent inability to complete assignments, or his lack of interest in finalizing some of his projects: "But while he was thus spending his time in the close research of subordinate branches of his art he carried only very few works to completion." Even during his lifetime, Leonardo's tendency to leave undertakings unfinished was legendary. When Pope Leo X heard that Leonardo was fussing over various recipes for varnishes instead of actually painting, he apparently complained, "Alas! This man will never do anything, for he begins by thinking about the end before the beginning of his work."

To Leonardo, ostensibly, each painting was also a scientific experiment, both in terms of correctly presenting the subject matter being portrayed and with regard to the execution of the painting itself. It was an exercise in curiosity as well: "Study the science of art; Study the art of science; Learn to see," he said. Concerning the physical implementation of painting techniques, some of his paintings, *The Last Supper* (Figure 5) for instance, failed to last—the paint was probably flaking off the wall even in Leonardo's lifetime. From a different standpoint, however, *The Last Supper* is a resounding success and an extraordinary masterpiece. It represents a brilliant study in perspective and in the effective use of light and shadow. One can even perceive in the spreading of the emotional wave created by Christ's words "One of you shall betray me" the lessons Leonardo had learned from his observations of the propagation of waves in water.

Figure 5

Here, however, lies another contradiction. The same person who was capable of so delicately capturing the most subtle human moods and emotions (also seen in *The Virgin and Child with St. Anne* and the celebrated *Mona Lisa*) revealed almost nothing of his personal feelings in his extensive writings. If Leonardo was as curious about his own internal world as he was about the external one, he chose not to let us in.

Amazed and Curious

Many excellent studies have attempted to use Leonardo's numerous notebooks, detailed comments, and elaborate drawings to assess his actual achievements and the degree to which he produced genuinely new discoveries in science and technology. Others have sought to critically evaluate the originality of his contributions, given the existing knowledge at the time. I am interested in different questions that are equally enticing: What was it that made Leonardo curious, and why? What did he do to satisfy his curiosity? At what point, if any, did he actually lose interest in a particular topic? Rather than being concerned with Leonardo's successes and failures in his scientific endeavors and his artistic and engineering projects, or with the extent to which he did or did not influence scientific progress or the course of art history, I am curious about what caught his fancy, what motivated him, and how he responded to such stimuli.

Leonardo's personal notebooks are an excellent point of departure for addressing these questions, for the following main reasons. First, the extant 6,500 pages of notes and drawings probably represent only part of his output, estimated by some researchers to be 15,000 pages. Since Leonardo began to keep notebooks only around the age of thirty-five, he must have filled on average, about a page and a half every day for three decades! It would seem that loading pages with painstaking drawings and sophisticated notes describing his ideas, interests, and contemplations (mostly written with his left hand, from right to left, and in mirror image) was one of Leonardo's most cherished occupations. Amazingly, the existing body of Leonardo's drawings alone is about four times that of even the most productive sixteenth-century draftsman. Second, aside from this apparent obsession with analyzing and documenting every rational thought, the actual content of the notebooks covers such topics as anatomy, vision and optics, astronomy, botany, geology, physical geography, the flight of birds, movement and weight, the properties and motion of water, and a confounding variety of imaginative inventions for both peaceful purposes and warfare. Finally, couple the vast scientific and technological substance of the notebooks to the reality that Leonardo used those very same pages for incessant comments on artistic matters, such as color, light and shade, perspective, precepts of the painter, and sculpture and architecture. The picture that emerges is as clear, and at the same time as enigmatic, as some of the elements in Leonardo's paintings themselves.

Leonardo was curious about almost *everything* in the complex world surrounding him, and his compulsive note taking and drawing phenomenon, such as the propagation of waves in a pool, his visually inspired mind immediately translated the problem into that of a geometrical shape. Concomitantly, his wandering curiosity guided him to an entire menagerie of other natural phenomena or human-made devices in which similar curves or geometrical structures appear. For example, when magnified, the drawing shows the branches of the tree metamorphosing into a network of veins, seen through the old man's cape.

That was not the only time that Leonardo examined branching systems. He noticed those structures across a wide range of different disciplines, from the tributaries of rivers, through the stems of plants, to the blood vessels in the human body. The culmination of the dizzying mental journey that led to the creation of Figure 6 was the abstraction of a common feature from a collection of seemingly disparate observations. In Leonardo's own words, "Painting compels the mind of the painter to transform itself into the very mind of Nature to become an interpreter between Nature and the art. It explains the causes of Nature's manifestations as compelled by its laws."

Given the scientific backdrop against which Leonardo was working, this last statement is truly remarkable. He is asserting that Nature is governed by certain laws! This is about a century before Galileo articulated his law of inertia and almost two centuries before Newton formulated his laws of motion and gravitation. Was Leonardo also sufficiently curious to wonder what those laws might be? You can bet he was. Unfortunately, the scientific tradition of his time did not yet include the statement of a coherent hypothesis and the testing of that hypothesis through a series of carefully constructed experiments or observations. Instead, Leonardo tended to simply list all the questions he could think of, probably in the order in which those popped into his relentlessly curious mind, and then to address only a few of those through more careful inspections. Sometimes, however, what he discovered was a fusion of his artistic and scientific visions. For instance, his drawings of water flows often resemble braids of hair, and the wavy hair in his painting of Ginevra de' Benci (Figure 7) looks like turbulent water. Still, from a multitude of diverse studies, Leonardo did emerge with two major realizations. First, he concluded that repeated, quantitative experiments and observations were absolutely crucial for the incontrovertible detection of the patterns associated with natural phenomena. In his words, "This experiment should be made many times so that no accident may occur to hinder or falsify this proof, for the experiment might be false whether it deceived the investigator or not." This may partially explain the fact that Leonardo's notebooks contain many repetitions, even though his quantitative measurements are approximate at best. His second remarkable deduction was that the human mind could gain access to the governing laws of nature through the language of mathematics. Accordingly, much of Leonardo's work during the last two decades of his life was devoted to the pursuit of general geometrical laws that would apply to phenomena ranging from the currents in rivers to light and shade and the intricacies of human anatomy.

Figure 7

Following in Plato's and the Neoplatonists' footsteps, geometry became Leonardo's guiding light on the pathway connecting the human observer to the explanations and interpretations of the universe, even if that connection was more a matter of belief than relying on a solid empirical foundation. First, there was the geometry associated with the process of vision, then the geometrical rules or laws that the natural world was supposed to obey, and finally the nature of the mathematical language itself, which to Leonardo was the basic Euclidean geometry we learn at school. Concerning the propagation of light, for instance, Leonardo drew a series of triangles ("pyramids" in his terminology) and concluded (incorrectly in quantitative terms) that the light intensity decreases proportionally to the inverse of the distance from the source, that is, that a source twice as distant would appear half as bright. In reality, the brightness decreases with an inverse square law: at twice the distance a light source appears four times dimmer, at three times the distance nine times dimmer, and so on. He applied similar laws to what he defined as the four "powers" of nature: "movement, force, weight, and percussion."

For branching systems, such as trees, Leonardo introduced an original law, according to which the sum total of the cross-sectional areas at each level must be equal. For instance, he inferred that the sum of the areas of the cross sections of the smallest twigs in the periphery must be equal to the cross-sectional area of the tree trunk. While the idea underlying this pronouncement was ingenious and correct (Leonardo deduced that what flows in must flow out), he neglected the fact that the speed of the flow could vary along the way, and consequently his law was not accurate. From our perspective, however, the important point is not whether Leonardo's rules were correct or whether he knew enough mathematics to even attempt to formulate precise laws. The crucial element is the fact that he used a geometrical representation of rules at all. Moreover, he contended that "there is no certainty where one cannot apply any of the mathematical sciences or any of those which are connected to the mathematical sciences." This exceptional insight is comparable to Galileo's famous dictum "We cannot understand it [the universe] if we do not first learn the language and grasp the characters in which it is written. It is written in the language of mathematics, and the characters are triangles, circles and other geometrical figures." But

Galileo was a mathematician. Astonishingly, Leonardo, who was rather weak in mathematics, except perhaps in some aspects of curvilinear geometry (and a few elements he learned from his mathematician friend Luca Pacioli), already believed that the only way to understand the universe with some certainty was through mathematics. Consequently, he was bold enough to write, "No man who is not a mathematician should read the elements of my work"—a phrase very reminiscent of the legendary inscription that supposedly hung above the door to Plato's Academy: "Let no one destitute of geometry enter."

One of Leonardo's key comprehensions was that, irrespective of what the laws were, they were in some sense *universal.* That is, the same laws applied to all the "powers," whether those powers acted in the macrocosm of the world at large, in the microcosm represented by the human body, or in the workings of human-made machines. He wrote, "Proportion is not only found in numbers and measurements but also in sounds, weights, times, spaces, and whatsoever powers there be." Similarly, in his correct anticipation of Newton's third law of motion (that any reaction is equal in strength but opposite in direction to the action), Leonardo wrote, "An object offers as much resistance to the air as the air does to the object." This was immediately followed by "And it is the same with water."

Eventually, as part of his aspiration to find general laws or broad-ranging distinctive features and to apply those to specific situations, Leonardo turned his attention to the human body. In that arena, as University of Toronto professor of anatomy James Playfair McMurrich writes, "If . . . the impulse to the new movement in anatomy came from the artists, Leonardo may well be recognized as its originator and Vesalius [the anatomist Andreas Vesalius, who was born five years before Leonardo's death] as its great protagonist."

From this simple but fundamental appreciation, he went on to discover parts of the heart not even mentioned by Galen, most notably the atria. Leonardo correctly identified these as contracting chambers that push blood into the ventricles. At an even more basic level in terms of the underlying physical processes involved, he suggested that the heat, which he regarded as a signature of life, is generated by friction with the ebb and flow of the blood. He then used this idea to explain the association of fever with a more rapid pulse: "The more rapidly the heart moves the more the heat is increased, as the pulse of the febrile, moved by the beating of the heart, teaches us."

In the spirit of exploration, Leonardo employed a combination of ingenious experiments and fastidious observations to unscramble the functions of various parts of the heart. In some of his tests, he creatively represented the aorta by a glass model and the ventricle by a flexible bag. On the observational side, he used analogues of blood flow by following the motion of seeds in a fluid, in the same way he had previously investigated the flow of water in rivers.

The chief obstacle that ultimately prevented Leonardo from discovering and understanding the entire concept and mechanism of blood circulation was probably the fact that he had never witnessed a dissection of the chest of a live human being. Consequently, he missed the opportunity to see with his own eyes what he surely would have regarded as a wonderful machine—the human heart—while it was still beating. The comprehensive understanding of the circulatory system was left for the English physician William Harvey, more than a century later. What Leonardo did accomplish through his tenacious scrutiny was still quite remarkable. Single-handedly, he removed almost all of Galen's unnatural elements from the description of the life processes, and he placed life itself squarely within the realm of general physical laws. His clear and prescient judgment marked the dawn of the scientific awakening that was about to follow: "Why

Nature cannot give the power of movement to animals without mechanical instruments, as is shown by me in this book on the works of movement which nature has created in animals. And for this reason I have drawn up the rules of the four powers of nature."

Simply put, Leonardo replaced the mystic black bile, faculties, and spirits that permeated the writings of Galen, Avicenna, de Luzzi, and others, with his physical powers of movement, weight, force, and percussion—the building blocks of mechanics. He further used these mechanical concepts to demystify a whole host of physiological processes. For instance, he correctly described the pulse thus: "Expansion occurs when they [the vessels] receive the excessive quantity of blood, and contraction is due to the departure of the excess of blood they have received."

There is no doubt that in spite of the fact that many of his methods were nonscientific by modern standards, in his striving to explain phenomena through physical rather than supernatural effects, Leonardo represented the burgeoning of modern thinking about the true nature of scientific research. His was the type of observation-based, empirical exploration that eventually led to such curious and towering scientists as Galileo, Newton, Michael Faraday, and Darwin, and empiricist philosophers such as John Locke, who argued that knowledge is achieved through the perception of the senses and rational contemplation rather than being planted in the mind by a divine power.

I Have Seen a Curious Child

What was it, then, that distinguished Leonardo from his predecessor anatomists, hydraulicists, botanists, and technologists? And why did he, trained as an artist, succeed in producing scientific and technological discoveries that, even if occasionally wrong, were at times far ahead of those of even his professional contemporaries?

After all, the opportunities he had to become involved in, say, anatomical studies, were available to any other scientist and artist of his time. The answer to these questions is actually so simple that it sounds almost banal: Leonardo had an unquenchable curiosity which he attempted to satisfy directly through his own observations rather than by relying on statements by figures of authority. It was neither the result of a particular investigation nor even the method used in any specific inquiry that significantly distinguished Leonardo from his contemporaries. It was the fact that he considered almost every natural phenomenon interesting and worthy of study.

What if his observations did not agree with prevailing wisdom? Leonardo had an unambiguous answer: in that case it was the theory that needed to be revised or altogether rejected. In his words, "Wrongly do men blame innocent experience, accusing her of deceit and false results. . . . Experience is not at fault, it is only our judgment that is in error in promising itself from experience things that are not in her power!"

Take the field of anatomy as an example. Whereas to many medieval anatomists, dissection served merely as a demonstration of Avicenna's teachings, Leonardo dissected to explore and prove things to himself. Similarly, in mechanics, while Leonardo's earliest writings did consider some contemporary ideas for perpetual motion machines, by 1494, following results from his own experiments, he had convinced himself that at least some designs would not work: "Oh! Speculators about perpetual motion, how many vain chimeras have you created in the like quest. Go and take your place with the seekers after gold!"

As I have already noted, there are a few personality characteristics of Leonardo that deserve special attention. First, there was the apparent contradiction between his being rather reclusive and his obsessive documentation of every conception, presumably at least partially for others to eventually read. One of the speculations about his mirror writing is that he was trying to make it harder for people to read his notes, but as we shall soon see, that may not have been the case.

Second, there was the discrepancy between Leonardo the cold, seemingly emotionless analyzer of the natural world and Leonardo the tender, almost romantic painter of exquisitely nuanced human feelings. In his entire oeuvre, only once did he truly reveal an aspect of his emotional side in writing (as he regularly did in painting). In his description of a journey he took to the mountains he wrote:

> Having wandered some distance among gloomy rock, I came to the entrance of a great cavern, in front of which I stood some time, astonished and unaware of such a thing. Bending my back into an arch I rested my left hand on my knee and held my right hand over my down-cast and contracted eye brows; often bending first one way and then the other, to see whether I could discover anything inside, and this being forbidden by the deep darkness within, and after having remained there some time, two contrary emotions arose in me, fear and desire—fear of the threatening dark cavern, desire to see whether there were any marvelous things within it.

As we shall see in chapter 4, unknowingly Leonardo captured here one of the suggested characteristics of curiosity: an ambivalent combination of excitement and apprehension. Up to a point, uncertainty about a topic enhances curiosity. After that point, however, the uncertainty becomes so overwhelming that it can produce discomfort, or even fear.

Leonardo's passion for discovering new things within the yet unexplored parts of the world is also reminiscent of another staggeringly brilliant but otherwise socially challenged individual, Isaac Newton. Shortly before his death, Newton said, "I do not know what I may appear to the world; but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now

Simon & Schuster
1230 Avenue of the Americas
New York, NY 10020
www.SimonandSchuster.com

First Simon & Schuster hardcover edition July 2017

Interior design by Paul Dippolito
Jacket Illustration by Jason Heuer

Library of Congress Cataloging-in-Publication Data

Names: Livio, Mario, 1945– author.
Title: Why? : what makes us curious / by Mario Livio.
Description: New York : Simon & Schuster, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2016040604| ISBN 9781476792095 | ISBN