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Feature Article

Leonardo da Vinci – The Scientist

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Abstract. To celebrate the 500th anniversary of Leonardo's death we gladly republish, with permission, one chapter from Walter Isaacson's book "Leonardo da Vinci" by Simon & Schuster. Leonardo was born as a natural child on April 15, 1452 in Anchiano, a handful of houses near Vinci, close to Florence. He died on May 2, 1519, in the grandiose castle of Clos Lucé near Amboise, not far from Tours in the middle of France. A free spirit, a true master in inter- and multisciplinarity, indifferent to taboos and scientific dogmas, one of the fathers of what we call the "scientific method". Obsessed by experience and observation, eager devourer of the first scientific printed books, he understood and practiced the correct balance between experiments and theories. In particular, on the role of experience and mathematics he wrote in the "Treatise on Painting": "Nissuna umana investigazione si pò dimandare vera scienzia s'essa non passa per le matematiche dimostrazioni, e se tu dirai che le scienzie, che principiano e finiscono nella mente, abbiano verità, questo non si concede, ma si niega, per molte ragioni, e prima, che in tali discorsi mentali non accade esperienzia, sanza la quale nulla dà di sé certezza." (No human investigation can be termed true science if it is not capable of mathematical demonstration. If you say that the sciences which begin and end in the mind are true, I do not agree, but deny it for many reasons, and foremost among these the fact that the test of experiment is absent from these exercises of the mind, and without these there is no assurance of certainty).

Keywords. Leonardo, scientific method, epistemology, empirism.

TEACHING HIMSELF

Leonardo da Vinci liked to boast that, because he was not formally educated, he had to learn from his own experiences instead. It was around 1490 when he wrote his screed about being "a man without letters" and a "disciple of experience," with its swipe against those who would cite ancient wisdom rather than make observations on their own. "Though I have no power to quote from authors as they have," he proclaimed almost proudly, "I shall rely on a far more worthy thing—on experience."[1] Throughout his life, he would repeat this claim to prefer experience over received scholarship. "He who has access to the fountain does not go to the water-jar," he wrote.[2] This made him different from the archetypal Renaissance Man, who embraced the rebirth of wisdom that came from rediscovered works of classical antiquity.

The education that Leonardo was soaking up in Milan, however, began to soften his disdain for handed-down wisdom. We can see a turning point in the early 1490s, when he undertook to teach himself Latin, the language not only of the ancients but also of serious scholars of his era. He copied page after page of Latin words and conjugations from textbooks of his time, including one that was used by Ludovico Sforza's young son. It appears not to have been an enjoyable exercise; in the middle of one notebook page where he copied 130 words, he drew his nutcracker man scowling and grimacing more than usual (Figure 49). Nor did he ever master Latin. For the most part his notebooks are filled with notes and transcriptions from works available in Italian.

In that regard, Leonardo was born at a fortunate moment. In 1452 Johannes Gutenberg began selling Bibles from his new printing press, just when the development of rag processing was making paper more readily available. By the time Leonardo became an apprentice in Florence, Gutenberg's technology had crossed the Alps into Italy. Alberti marveled in 1466 about "the German inventor who has made it possible, by certain pressings down of characters, to have more than two hundred volumes written out in a hundred days from the original, with the labor of no more then three men." A goldsmith from Gutenberg's hometown of Mainz named Johannes de Spira (or Speyer) moved to Venice and started Italy's first major commercial publishing house in 1469; it printed many of the classics, starting with Cicero's letters and Pliny's encyclopedic *Natural History*, which Leonardo bought. By 1471 there were printing shops also in Milan, Florence, Naples, Bologna, Ferrara, Padua, and Genoa. Venice became the center of Europe's publishing industry, and by the time Leonardo visited in 1500, there were close to a hundred printing houses there, and two million volumes had come off their presses.[3] Leonardo thus was able to become the first major European thinker to acquire a serious knowledge of science without being formally schooled in Latin or Greek.

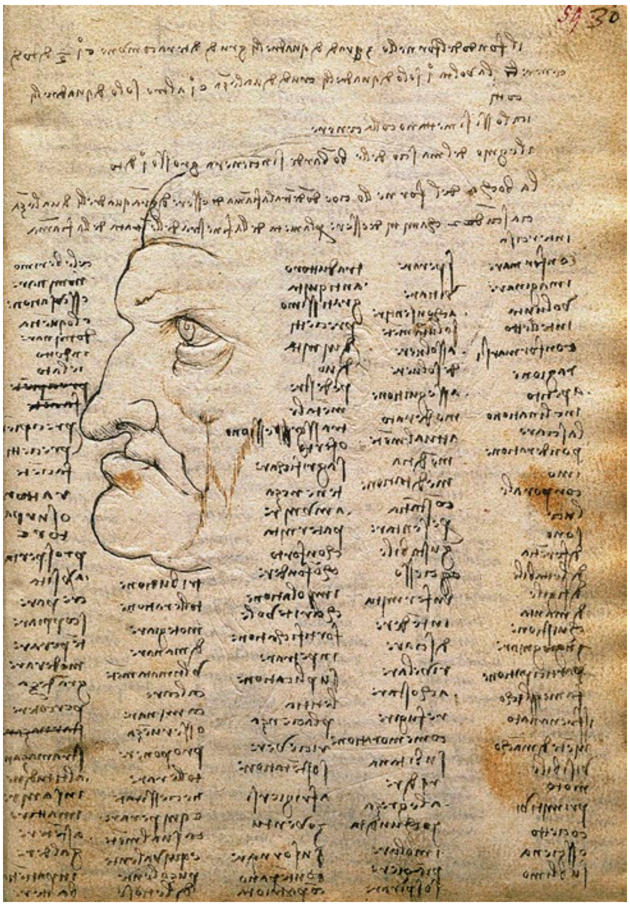

Figure 49. Trying to learn Latin, with a grimace.

His notebooks are filled with lists of books he acquired and passages he copied. In the late 1480s he itemized five books he owned: the Pliny, a Latin grammar book, a text on minerals and precious stones, an arithmetic text, and a humorous epic poem, Luigi Pulci's *Morgante*, about the adventures of a knight and the giant he converted to Christianity, which was often performed at the Medici court. By 1492 Leonardo had close to forty volumes. A testament to his universal interests, they included books on military machinery, agriculture, music, surgery, health, Aristotelian science, Arabian physics, palmistry, and the lives of famous philosophers, as well as the poetry of Ovid and Petrarch, the fables of Aesop, some collections of bawdy doggerels and burlesques, and a fourteenth-century operetta from which he drew part of his bestiary. By 1504 he would be able to list seventy more books, including forty works of science, close to fifty of poetry and literature, ten on art and architecture, eight on religion, and three on math.[4]

He also recorded at various times the books that he hoped to borrow or find. "Maestro Stefano Caponi, a physician, lives at the Piscina, and has Euclid," he noted. "The heirs of Maestro Giovanni Ghiringallo have the works of Pelacano." "Vespucci will give me a book of Geometry." And on a to-do list: "An algebra, which the Marliani have, written by their father. A book, treating of Milan and its churches, which is to be had at the last stationers on the way to Corduso." Once he discovered the University of Pavia, near Milan, he used it as a resource: "Try to get Vitolone, which is in the library at Pavia and deals with mathematics." On the same to-do list: "A grandson of Gian Angelo's, the painter, has a book on water which was his father's. Get the Friar di Brera to show you *de Ponderibus*." His appetite for soaking up information from books was voracious and wide-ranging.

In addition, he liked to pick people's brains. He was constantly peppering acquaintances with the type of questions we should all learn to pose more often. "Ask Benedetto Portinari how they walk on ice in Flanders," reads one memorable and vivid entry on a to-do list. Over the years there were scores of others: "Ask Maestro Antonio how mortars are positioned on bastions by day or night. Find a master of hydraulics and get him to tell you how to repair a lock, canal and mill in the Lombard manner. Ask Maestro Giovannino how the tower of Ferrara is walled without loopholes."[5]

Thus Leonardo became a disciple of both experience and received wisdom. More important, he came to see that the progress of science came from a dialogue between the two. That in turn helped him realize that knowledge also came from a related dialogue: that between experiment and theory.

CONNECTING EXPERIMENT TO THEORY

Leonardo's devotion to firsthand experience went deeper than just being prickly about his lack of received wisdom. It also caused him, at least early on, to minimize the role of theory. A natural observer and experimenter, he was neither wired nor trained to wrestle with abstract concepts. He preferred to induce from experiments rather than deduce from theoretical principles. "My intention is to consult experience first, and then with reasoning show why such experience is bound to operate in such a way," he wrote. In other words, he would try to look at facts and from them figure out the patterns and natural forces that caused those things to happen. "Although nature begins with the cause and ends with the experience, we must follow the opposite course, namely begin with the experience, and by means of it investigate the cause."[6]

As with so many things, this empirical approach put him ahead of his time. Scholastic theologians of the Middle Ages had fused Aristotle's science with Christianity to create an authorized creed that left little room for skeptical inquiry or experimentation. Even the humanists of the early Renaissance preferred to repeat the wisdom of classical texts rather than test it.

Leonardo broke with this tradition by basing his science primarily on observations, then discerning patterns, and then testing their validity through more observations and experiments. Dozens of times in his notebook he wrote some variation of the phrase "this can be proved by experiment" and then proceeded to describe a real-world demonstration of his thinking. Foreshadowing what would become the scientific method, he even prescribed how experiments must be repeated and varied to assure their validity: "Before you make a general rule of this case, test it two or three times and observe whether the tests produce the same effects."[7]

He was aided by his ingenuity, which enabled him to devise all sorts of contraptions and clever methods for exploring a phenomenon. For example, when he was studying the human heart around 1510, he came up with the hypothesis that blood swirled into eddies when it was pumped from the heart to the aorta, and that was what caused the valves to close properly; he then devised a glass device that he could use to confirm his theory with an experiment (see chapter 27). Visualization and drawing became an important component of this process. Not comfortable wrestling with theory, he preferred dealing with knowledge that he could observe and draw.

But Leonardo did not remain merely a disciple of experiments. His notebooks show that he evolved. When he began absorbing knowledge from books in the 1490s, it helped him realize the importance of being guided not only by experiential evidence but also by theoretical frameworks. More important, he came to understand that the two approaches were complementary, working hand in hand. "We can see in Leonardo a dramatic attempt to appraise properly the mutual relation of theory to experiment," wrote the twentieth-century physicist Leopold Infeld.[8]

His proposals for the Milan Cathedral tiburio show this evolution. To understand how to treat an aging cathedral with structural flaws, he wrote, architects need to understand "the nature of weight and the propensities of force." In other words, they need to understand physics theories. But they also need to test theoretical principles against what actually works in practice. "I shall endeavor," he promised the cathedral administrators, "to satisfy you partly with theory and partly with practice, sometimes showing effects from causes, sometimes affirming principles with experiments." He also pledged, despite his early aversion to received wisdom, to "make use, as is convenient, of the authority of the ancient architects." In other words, he was advocating our modern method of combining theory, experiment, and handed-down knowledge—and constantly testing them against each other.[9]

His study of perspective likewise showed him the importance of joining experience with theories. He observed the way objects appear smaller as they get more distant. But he also used geometry to develop rules for the relationship between size and distance. When it came time to describe the laws of perspective in his notebooks, he wrote that he would do so "sometimes by deduction of the effects from the causes, and sometimes arguing the causes from the effects."[10]

He even came to be dismissive of experimenters who relied on practice without any knowledge of the underlying theories. “Those who are in love with practice without theoretical knowledge are like the sailor who goes onto a ship without rudder or compass and who never can be certain whither he is going,” he wrote in 1510. “Practice must always be founded on sound theory.”[11]

As a result, Leonardo became one of the major Western thinkers, more than a century before Galileo, to pursue in a persistent hands-on fashion the dialogue between experiment and theory that would lead to the modern Scientific Revolution. Aristotle had laid the foundations, in ancient Greece, for the method of partnering inductions and deductions: using observations to formulate general principles, then using these principles to predict outcomes. While Europe was mired in its dark years of medieval superstition, the work of combining theory and experiment was advanced primarily in the Islamic world. Muslim scientists often also worked as scientific instrument makers, which made them experts at measurements and applying theories. The Arab physicist Ibn al-Haytham, known as Alhazen, wrote a seminal text on optics in 1021 that combined observations and experiments to develop a theory of how human vision works, then devised further experiments to test the theory. His ideas and methods became a foundation for the work of Alberti and Leonardo four centuries later. Meanwhile, Aristotle’s science was being revived in Europe during the thirteenth century by scholars such as Robert Grosseteste and Roger Bacon. The empirical method used by Bacon emphasized a cycle: observations should lead to a hypothesis, which should then be tested by precise experiments, which would then be used to refine the original hypothesis. Bacon also recorded and reported his experiments in precise detail so that others could independently replicate and verify them.

Leonardo had the eye and temperament and curiosity to become an exemplar of this scientific method. “Galileo, born 112 years after Leonardo, is usually credited with being the first to develop this kind of rigorous empirical approach and is often hailed as the father of modern science,” the historian Fritjof Capra wrote. “There can be no doubt that this honor would have been bestowed on Leonardo da Vinci had he published his scientific writings during his lifetime, or had his Notebooks been widely studied soon after his death.”[12]

That goes a step too far, I think. Leonardo did not invent the scientific method, nor did Aristotle or Alhazen or Galileo or any Bacon. But his uncanny abilities to engage in the dialogue between experience and theory made him a prime example of how acute observations, fanatic curiosity, experimental testing, a willingness to question dogma, and the ability to discern patterns across disciplines can lead to great leaps in human understanding.

PATTERNS AND ANALOGIES

In lieu of possessing abstract mathematical tools to extract theoretical laws from nature, the way Copernicus and Galileo and Newton later did, Leonardo relied on a more rudimentary method: he was able to see patterns in nature, and he theorized by making analogies. With his keen observational skills across multiple disciplines, he discerned recurring themes. As the philosopher Michel Foucault noted, the “protoscience” of Leonardo’s era was based on similarities and analogies.[13]

Because of his intuitive feel for the unity of nature, his mind and eye and pen darted across disciplines, sensing connections. “This constant search for basic, rhyming, organic form meant that when he looked at a heart blossoming into its network of veins he saw, and sketched alongside it, a seed germinating into shoots,” Adam Gopnik wrote. “Studying the curls on a beautiful woman’s head he thought in terms of the swirling motion of a turbulent flow of water.”[14] His drawing of a fetus in a womb hints at the similarity to a seed in a shell.

When he was inventing musical instruments, he made an analogy between how the larynx works and how a glissando recorder could perform similarly. When he was competing to design the tower for Milan’s cathedral, he made a connection between architects and doctors that reflected what would become the most fundamental analogy in his art and science: that between our physical world and our human anatomy. When he dissected a limb and drew its muscles and sinews, it led him to also sketch ropes and levers.

We saw an example of this pattern-based analysis on the “theme sheet,” where he made the analogy between a branching tree and the arteries in a human, one that he applied also to rivers and their tributaries. “All the branches of a tree at every stage of its height when put together are equal in thickness to the trunk below them,” he wrote elsewhere. “All the branches of a river at every stage of its course, if they are of equal rapidity, are equal to the body of the main stream.”[15] This conclusion is still known as “da Vinci’s rule,” and it has proven true in situations where the branches are not very large: the sum of the cross-sectional area of all branches above a branching point is equal to the cross-sectional area of the trunk or the branch immediately below the branching point.[16]

Another analogy he made was comparing the way that light, sound, magnetism, and the percussion reverberations caused by a hammer blow all disseminate in a radiating pattern, often in waves. In one of his notebooks he made a column of small drawings showing how each force field spreads. He even illustrated what happened when each type of wave hits a small hole in the wall; prefiguring the studies done by Dutch physicist Christiaan Huygens almost two centuries later, he showed the diffraction that occurs as the waves go through the aperture.[17] Wave mechanics were for him merely a passing curiosity, but even in this his brilliance is breathtaking.

The connections that Leonardo made across disciplines served as guides for his inquiries. The analogy between water eddies and air turbulence, for example, provided a framework for studying the flight of birds. "To arrive at knowledge of the motions of birds in the air," he wrote, "it is first necessary to acquire knowledge of the winds, which we will prove by the motions of water."[18] But the patterns he discerned were more than just useful study guides. He regarded them as revelations of essential truths, manifestations of the beautiful unity of nature.

CURIOSITY AND OBSERVATION

In addition to his instinct for discerning patterns across disciplines, Leonardo honed two other traits that aided his scientific pursuits: an omnivorous curiosity, which bordered on the fanatical, and an acute power of observation, which was eerily intense. Like much with Leonardo, these were interconnected. Any person who puts "Describe the tongue of the woodpecker" on his to-do list is overendowed with the combination of curiosity and acuity.

His curiosity, like that of Einstein, often was about phenomena that most people over the age of ten no longer puzzle about: Why is the sky blue? How are clouds formed? Why can our eyes see only in a straight line? What is yawning? Einstein said he marveled about questions others found mundane because he was slow in learning to talk as a child. For Leonardo, this talent may have been connected to growing up with a love of nature while not being overly schooled in received wisdom.

Other topics of his curiosity that he listed in his notebooks are more ambitious and require an instinct for observational investigation. "Which nerve causes the eye to move so that the motion of one eye moves the other?" "Describe the beginning of a human when it is in the womb."[19]And along with the woodpecker, he lists "the jaw of the crocodile" and "the placenta of the calf" as things he wants to describe. These inquiries entail a lot of work.[20]

His curiosity was aided by the sharpness of his eye, which focused on things that the rest of us glance over. One night he saw lightning flash behind some buildings, and for that instant they looked smaller, so he launched a series of experiments and controlled observations to verify that objects look smaller when surrounded by light and look larger in the mist or dark.[21] When he looked at things with one eye closed, he noticed that they appeared less round than when seen with both eyes, so he went on to explore the reasons why.[22]

Kenneth Clark referred to Leonardo's "inhumanly sharp eye." It's a nice phrase, but misleading. Leonardo was human. The acuteness of his observational skill was not some superpower he possessed. Instead, it was a product of his own effort. That's important, because it means that we can, if we wish, not just marvel at him but try to learn from him by pushing ourselves to look at things more curiously and intensely.

In his notebook, he described his method—almost like a trick—for closely observing a scene or object: look carefully and separately at each detail. He compared it to looking at the page of a book, which is meaningless when taken in as a whole and instead needs to be looked at word by word. Deep observation must be done in steps: "If you wish to have a sound knowledge of the forms of objects, begin with the details of them, and do not go on to the second step until you have the first well fixed in memory."[23]

Another gambit he recommended for "giving your eye good practice" at observations was to play this game with friends: one person draws a line on a wall, and the others stand a distance away and try to cut a blade of straw to the exact length of the line. "He who has come nearest with his measure to the length of the pattern is the winner."[24]

Leonardo's eye was especially sharp when it came to observing motion. "The dragonfly flies with four wings, and when those in front are raised those behind are lowered," he found. Imagine the effort it took to watch a dragonfly carefully enough to notice this. In his notebook he recorded that the best place to observe dragonflies was by the moat surrounding the Sforza Castle.[25] Let's pause to marvel at Leonardo walking out in the evening, no doubt dandily dressed, standing at the edge of a moat, intensely watching the motions of each of the four wings of a dragonfly.

His keenness at observing motion helped him overcome the difficulty of capturing it in a painting. There is a paradox, which goes back to Zeno in the fifth century BC, involving the apparent contradiction of an object being in motion yet also being at a precise place at a given instant. Leonardo wrestled with the concept of depicting an arrested instant that contains both the past and the future of that moment.

He compared an arrested instant of motion to the concept of a single geometrical point. The point has no length or width. Yet if it moves, it creates a line. "The point has no dimensions; the line is the transit of a point." Using his method of theorizing by analogy, he wrote, "The instant does not have time; and time is made from the movement of the instant."[26]

Guided by this analogy, Leonardo in his art sought to freeze-frame an event while also showing it in motion. "In rivers, the water that you touch is the last of what has passed, and the first of that which comes," he observed. "So with time present." He came back to this theme repeatedly in his notebooks. "Observe the light," he instructed. "Blink your eye and look at it again. That which you see was not there at first, and that which was there is no more."[27]

Leonardo's skill at observing motion was translated by the flicks of his brush into his art. In addition, while working at the Sforza court, he began channeling his fascination with motion into scientific and engineering studies, most notably his investigations into the flight of birds and machines for the flight of man.

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