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On the Art of Scientific Imagination

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Source: *Daedalus*, Vol. 125, No. 2, Managing Innovation (Spring, 1996), pp. 183-208

Published by: The MIT Press on behalf of American Academy of Arts & Sciences

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## NOTES FROM THE ACADEMY

The text of addresses given at the Stated Meetings of the American Academy of Arts and Sciences are generally printed in the Academy's *Bulletin*, distributed principally to Fellows and Foreign Honorary Members of the Academy. Because the *Bulletin*'s format is not one designed to accommodate many detailed illustrations, and because the communication delivered by Professor Gerald Holton at the House of the Academy, like others recently given, raised such interest among those who heard it, a decision was made to make it more widely available through publication in the Academy's journal, *Dædalus*. This practice, followed very occasionally in the past, has much to recommend it and may be pursued more frequently in the future. [S.R.G.]

*Gerald Holton*

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### On the Art of Scientific Imagination

**W**HEN THE ACADEMY'S PRESIDENT asked if I would speak on Saint Valentine's Day, I gladly accepted the honor. But even if mutual affection is to be the order of the day, I face a dilemma. In this audience there are scientists who know the art of scientific imagination so well that it may seem that I am only bringing owls to Athens. Yet there are also others here to whom the matter may be unfamiliar. It is a problem for many speakers at our meetings, and was so even back in ancient Athens

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*Presented at the February 14, 1996 Stated Meeting of the American Academy of Arts and Sciences. Gerald Holton is Professor of Physics and Professor of History of Science, Emeritus at Harvard University.*

itself. That is why Pericles began his famous oration by explaining that he would try to find “a proper sense of balance” to avoid repeating things to those who “know the facts” and yet not lose all the others. His solution, as Thucydides quotes him, was to focus on what he called “the fairest gift of love,” namely the courageous deeds done on behalf of their society and their splendidly monumented city. Pericles added: “What I prefer is that you look at the greatness of the city, and should fall in love with her.”

This is also my theme today, transposed to the republic of science and its monuments. I want to focus on the question of how scientists, devoting themselves to some of the most difficult problems, *can succeed at all*. The physicist Eugene Wigner coined the phrase, “the unreasonable effectiveness of mathematics in the natural sciences.” But we must wonder about the unreasonable effectiveness of science itself, especially in the early, nascent phase of an individual’s research. One can call that phase “Private Science,” before the results are cleaned up and, as Louis Pasteur put it, are made to look inevitable—that is, before they become science in that other sense, namely “Public Science,” in which the profession’s organized skepticism and other norms dominate.

Of course, the primary tools of the trade, which a scientist can be taught to use, are indispensable: perseverance, the use of one’s rational faculties while forming and testing hypotheses, mathematics and instrumentation, judicious modeling, looking skeptically for flaws or disconfirmations, etc. But in truth, all these are not sufficient to explain the daring and risky leaps of speculation that are often the crucial ingredient, or even the initial impetus, for a project. There must be a second, complementary set of forces at work—an *art* of the imagination.

Most scientists are reluctant to talk about it, perhaps because that art is idiosyncratic, seemingly inaccessible, and varies among fields; in any case, by keeping one’s personal struggle out of the literature, one makes it easier to reach consensus about the final results. But there *are* a few hints. In a famous speech of 1918, Albert Einstein suggested that the elusive, additional element needed for high achievement in science is a “state of feeling” in the researcher, which he called “akin to that of the religious worshipper or of one who is in love,” arising not from a deliberate decision or program but from a personal necessity. Others are more down

to earth. With eloquent simplicity P. W. Bridgman wrote, “The scientific method, as far as it is a method, is nothing more than doing one’s damndest with one’s mind, no holds barred.” But as good as they are, neither remark nor the occasional anecdotal confession is much help for discovering what we are after. Peter Medawar put it this way, though a bit harshly: “It is of no use looking to scientific papers, for they not merely conceal but actively misrepresent the reasoning that goes into the work they describe. . . . Only unstudied evidence will do—and that means listening at the keyhole.”

So, onward to the keyhole. I shall attend to just three tools of the art of scientific imagination, none of which is explicitly taught in our science texts: the visual imagination, the analogical imagination, and the thematic imagination. My examples will be drawn from historic cases in physics, but one could harvest similar instances from other branches of science.

\* \* \*

I start with the *visual imagination* for two reasons: first, modern science in the very beginning entered through the eye, by watching the puzzling motions of celestial objects. Marjorie Nicolson, in her pioneering book *Science and Imagination*, went so far as to state: “We may perhaps date the beginning of modern thought from the night of January 7, 1610 when Galileo, by means of the instrument which he had developed [the telescope], thought he perceived new planets and new, expanded worlds.” And second, as we shall hear later, in our century the ability to visualize physical phenomena encountered a crisis of its own.

Galileo’s astronomical studies are a classic example of patient observation being translated into a mental model that had an explanatory visual component. The case has intrigued many scholars, from Erwin Panofsky in the 1950s to Samuel Edgerton, I. Bernard Cohen, Martin Kemp, and others in recent years; I shall borrow from all of them.

In 1609, two men, independently of each other, looked at our moon through a new invention from the Netherlands: the spyglass or, as it was later termed, the telescope. The first man, in July 1609, was Thomas Harriot of London, an accomplished but rather

reclusive mathematician and astronomer. The other man, several months later, was Galileo, a forty-five year old professor of mathematics at the University of Padua who had no definitive accomplishment to his credit. He had taught himself to grind lenses, and he made telescopes with successively higher magnification.

Luckily, we have some record of what each of these two men thought he observed, and it is instructive to compare their private notes, trying to understand the reasons for the great differences between them. Of course, both men knew that from the time of Aristotle's *De Caelo* and the *Metaphysica* the moon was thought to be made of a celestial substance, that it was a perfectly smooth sphere, the symbol of the incorruptible universe beyond Earth. In paintings since the Middle Ages, the moon had been a sign of the Immaculate Conception of the Virgin Mary (see *Figure 1*, page 195). But this was problematic. To the naked eye some areas of the real moon appeared to be darker than others. Thomas Harriot called it "that strange spottednesse." In Dante's *Paradiso*, the heavenly Beatrice has to calm Dante's puzzlement about those "dusky marks," which she does with an eloquent lecture on the current state of optics. By the seventeenth century, several ad hoc theories had sprung up to deal with the problem. But no one had reason to question the supposedly perfect sphericity of the moon.

Among Thomas Harriot's papers is a drawing in which he traces the division between the dark and illuminated portions of the moon, the so-called terminator (see *Figure 2*, page 195). But Harriot makes no comment on why he finds it to be not the smooth curve that one would expect on a perfect sphere but rather a jagged line. Harriot *sees*, but the current presuppositions make it difficult for him to undertake the intellectual transformation, to cross from sense experience to a new way of understanding.

Galileo enters the story in late November 1609. Through his telescope he carefully observed the moon for several weeks as it went through its phases, with the same skill of interpretive knowing that he used soon thereafter in studying Jupiter, Venus, the Milky Way, and the sunspots. It was risky to place much trust in a new instrument in such a charged context. The telescopes, and indeed the theory of optics itself, were primitive. The lenses had spherical and chromatic aberrations. Some who were allowed to look through Galileo's telescope failed to see what he was trying to

show. And in any case, philosophers, even his friend Cremonini, thought that any optical instrument would by its nature distort reality.

But Galileo's own confidence grew quickly. As his skillful ink-wash drawings in chiaroscuro style show (see *Figure 3*, page 195), he too saw the jagged line of the terminator; but he was also alert to an important new phenomenon, namely, numerous small, bright areas within the dark part of the moon, as well as many dark areas in the bright part. They changed in appearance during a period of 2 or 3 hours as the angle of the sunlight changed, and that led Galileo to the astonishing idea that those small bright and dark areas represented respectively prominences and cavities, analogous to the mountains and valleys on earth: "Bright ridges of mountains rise loftily out of the darkness." So, the moon's surface was irregular rather than smooth! Galileo calculated from the shadows cast by the peaks that some of the moon mountains must be higher than the Alps. He published these observations and interpretations in his *Sidereus Nuncius*, including a sort of "in-your-face" anti-Aristotelian exaggeration of the prominences and depressions at quadrature (see *Figure 4*, page 196). On January 7, 1610, he wrote that he now believed there was no qualitative difference between the earth and the moon. By January 15, he was certain of the existence of Jupiter's four moons, thereby disproving the Aristotelian theory that all motions in the heavens take place around the earth.

As Galileo's sensational findings spread through Europe, they transformed what other scientists saw. Thomas Harriot, who had earlier mistrusted the "circular astronomy" of Copernicus, raised his telescope again in July 1610; having now read Kepler's *Astronomia Nova* of 1609 and Galileo's book of 1610, he made a sketch of his new observation (see *Figure 5*, page 196). Now he, too, saw craters and other earth-like features and even some that were not in Galileo's published sketches. Harriot recognized a "mountainous moon." The meaning of the visual impressions had been changed by what Martin Kemp has termed "interpretive knowing."

Perhaps the most nagging question in this story is why Galileo and Harriot initially had such different responses when they studied the same moon. Part of the answer lies, of course, in Galileo's

greater readiness to consider a Copernican universe in which planets and satellites are essentially similar (although he did not become fully persuaded of it until his discovery of the moons around Jupiter). Other factors include Galileo's superb skill as an instrument-maker and experimenter, "replacing mere observations by measurements, involving routine procedures under standard conditions" (Alan Chalmers).

But a good bit of Galileo's advantage may well have been his prior training in visualization. A widely cultured man living in a country where Renaissance painting had captured the alert intellectuals, Galileo's first job application at age twenty-five had been to the Accademia del Disegno for a position teaching geometry to architects and linear perspective to painters and sculptors. It is very likely that Galileo, like all students at that Academy, had honed his visualization skills by studying how three-dimensional bodies appear to the eye and cast shadows under different illumination.

*Figure 6* (page 196) is an example from one of the popular texts used at the time, showing how prominences and depressions on reticulated spheres appear in light and shade. I find it very plausible, as several scholars have argued, that Galileo's skilled knowledge of Euclidean geometry helped influence his understanding of the shapes on the moon's surface—just as *non*-Euclidean geometry later was to lay the groundwork for the reception of the general relativity theory. And it must have delighted Galileo that his work enlightened not only scientists but also his friends among the humanists and artists, and above all Lodovico Cardi, called Cigoli, perhaps the most important Florentine painter of his time. In Cigoli's last major work, the frescoes in Santa Maria Maggiore in Rome, he placed the Virgin Mary on a Galilean moon that matched an illustration from the *Sidereus Nuncius* (see *Figure 7*, page 197). The heavens did not fall because of the progress of science but rather found a way to incorporate it. Later in his life, of course, Galileo paid dearly for it all.

Let me return for a moment to Marjorie Nicolson's remark, dating the onset of modernity from Galileo's telescopic studies. As Galileo's new view of the heavens spread throughout Europe, some celebrated that he had "overthrown all former astronomy" (Henry Wotton) and, with the decentering of the earth, had launched

a new philosophy as well. Others were deeply troubled by those very changes and their implication that the earth might be insignificant in that infinite expanse, that there might exist a plurality of other universes among the immensity of new stars revealed by Galileo's telescope. These threats against the old "order, proportion, and unity" (Nicolson) were mourned in John Donne's poem of 1611, "The First Anniversarie," containing the familiar lines "And new Philosophy calls all in doubt, / the Element of fire is quite put out..." and later, "...Is crumbled out againe to his Atomies / 'Tis all in peeces, all cohaerence gone; / All just supply, and all Relation." Ever since, scientists have found themselves between these contrary reactions: Cigoli's optimism on one side, and John Donne's pessimism on the other.

\* \* \*

Still, as in Galileo's day, the visual imagination has often been the crucial component in the mix that leads to new insights. In a letter to Jacques Hadamard, Einstein confessed: "The words or language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs or more or less clear images which can be 'voluntarily' reproduced and combined." It was as if he played in his mind with pieces of a jigsaw puzzle. To Max Wertheimer, Einstein reported, "I very rarely think in words at all. . . . I have it in a sort of survey, in a way visually."

Moreover, being primarily a theoretician rather than an experimenter, Einstein was able to employ his visualizing skill in his imaginative thought experiments, *Gedankenexperimente*, starting with the haunting picture at age sixteen of chasing or riding on a beam of light, which Einstein declared later in his autobiography to have contained the seed of his later work on special relativity.

The physics literature is full of highly visual thought experiments, from Newton's bucket experiment to Maxwell's Demon and Erwin Schrödinger's cat-in-a-box. Of all such examples, my favorite is the simplest. While on leave at the Institute for Advanced Study at Princeton, I came upon the twenty-odd file drawers of Einstein's papers and correspondence and was asked by the Einstein estate to organize this treasure trove into a usable archive.

Perhaps the most interesting among the thousands of documents was an unpublished manuscript from around 1920, where Einstein told how he came to invent the *general* theory of relativity. Reminiscing about his attempt in 1907 to fit Newtonian gravitation into the relativity theory, he writes:

At that point there came to me the happiest thought of my life, in the following form: just as in the case of the field produced by electromagnetic induction, the gravitational field has similarly only a relative existence. For if one considers an observer in free fall, for example, falling from a roof of a house, there exists for him during his fall no gravitational field. . . . If he releases any objects [no matter what their chemical or physical nature], they will remain in a state of rest relative to him. The observer is therefore justified to consider his own state as one of “rest.” [underlining in original]

This imagined scene contains the clue that the effects of accelerated motion and of gravity can be considered equivalent. Here Einstein found at last what he called “a mighty argument that the postulate of [special] relativity is to be extended” to general relativity.

\* \* \*

The examples of the power of visualization in the nascent phase of scientific discovery can be documented over and over again in the work of other artists of science, such as Faraday and Rutherford. When Niels Bohr adopted the imagery of the planetary system for his model of the atom in 1913, it was a real breakthrough, and Bohr himself was delighted to commission and use in his lectures colorful presentations for many of the atoms (e.g., in *Figure 8*, page 197).

But by the mid-1920s it became clear that it was dangerous to continue to think about atomic processes in terms of imagery originally invented for large-scale events, say, the motion of planets. New ways of imagining phenomena such as the spin of the electron or light as both a wave and a particle were needed. The easily visualized intuitions had become an obstacle to progress. One does not need to know much about Werner Heisenberg’s Uncertainty Principle to realize that those precisely drawn electron

orbits in Bohr's atomic models cannot exist in nature. This led Heisenberg from the mid-1920s on to propose a necessary but drastic solution, one which to this day makes it difficult for laymen to feel at home in the world of modern physics. Heisenberg totally eliminated the use of picturable models of the atom. A typical Heisenberg dictum asserted: "The program of quantum mechanics has to free itself first of all from these intuitive pictures. . . . The new theory ought above all to give up visualizability totally." The old *Anschaulichkeit* had to go.

In most other branches of science today the iconic imagination continues to be alive and well. But the quantum scientists had to gain a new kind of visualizability largely through mathematical rather than physical constructs, for example, through abstract diagrams that can be correlated with terms in mathematical equations. *Figure 9* (page 197) gives at least a hint of the new way. The top of the figure is the familiar textbook illustration, indicating in a visceral manner how two equally charged particles act on each other. It is a kind of momentary snapshot of a situation in space, the forces of repulsion acting somehow across the gap between the particles as they are straining to scatter away from each other. But it is much more meaningful to think of such a phenomenon taking place in space-time, caused by the mutual exchange of a virtual photon—a sort of messenger that mediates the interaction—between the two charged particles. The lower part of the figure indicates this new way in a diagram named after its proponent, Richard Feynman. In one of his early papers (1949), he introduced his new visualization of the scattering process; each leg of the space-time graph in *Figure 10* (page 198) corresponds at least qualitatively to a portion of the equation that describes the phenomenon in detail (see *Figure 11*, page 198).

In *Figure 10*, the fractured line from position 1 to 3 symbolizes the motion in space and time of the electron on the left; the line from 2 to 4 similarly indicates the path of the electron on the right during the same time interval. The two particles are approaching each other at the start, but then are repelled and separate. The mutual interaction that alters their paths is indicated by the absorption, by the electron at position 5 on the left, of a virtual quantum that had been emitted at an earlier time by the other particle at point 6. Or, as Feynman put it, that interaction can also

be thought of as the emission of the virtual quantum at point 5 on the left and its absorption, at an *earlier* time, at point 6 on the right!

As Silvan S. Schweber has noted in his fine new book, *QED*, one element of Feynman's genius was his "keen powers of visualization." In an interview, Feynman observed: "I see all the time visual things in association with what I am trying to do." But he added, in his self-deprecatory way, "The diagram is really in a certain sense the picture that comes from trying to clarify visualization, which is a half-baked kind of vague [thing], mixed with symbols. It is very difficult to explain, because it is not clear." It was clear enough to have become a standard tool in the mind of generations of physicists that followed. Nevertheless, as Feynman also said, "in the end, the mathematics can take over and can be more efficient. . . than the picture."

\* \* \*

I must now, alas more briefly, turn to two of the other helpers of the imagination. One is the use of analogy. This might surprise you. After all, philosophers have long warned that such a technique of thought can have no good purpose in science. The *Dictionary of Modern Thought* declares that analogy "is a form of reasoning that is peculiarly liable to yield false conclusions from true premises." Indeed, analogy and its close cousin, metaphor, have been called the essence of poetry. They work through illusion. Surely the business of scientists is precisely the opposite. And yet, happily, they use these tools frequently, often with great success, unconstrained by the vast literature on metaphor and analogy in literary criticism and philosophy.

We have already seen analogies at work: when Galileo compared the structures on the moon to the Alps on earth, when Bohr availed himself of the image of the solar system for his atom, when Einstein's happiest thought—that the gravitational field has "only a relative existence," just as the electric field does—came to him. To imagine and speak about the world invisible to us, we populate it with anthropomorphic and everyday concepts, almost by necessity. Think of Mendeleev's families of elements; of Rutherford's and Soddy's long chains of parent, daughter, and granddaughter

nuclides as the atoms decay, each with its own life or rather at least a half-life; of the very words “wave” and “particle” applied to subatomic phenomena; of concepts such as the flow of heat or of electricity; of lines of force in a field; of all those metaphors, particularly the military ones in medicine—invasion, attack, defense—and elsewhere in the sciences, e.g., Darwin’s Tree of Life, or the tangled bank; and before that, Newton’s centers of attraction, his clockwork universe, and on and on. (As Aristotle said in the *Poetics*: “But the greatest thing by far is to be a master of metaphor. It is the one thing that cannot be learned from others; it is also a sign of genius, since a good metaphor implies an intuitive perception of the similarity in dissimilars.”)

A grand master among analogists was Enrico Fermi. Early in 1934, he was working with Emilio Segrè and Edoardo Amaldi on the effects of pressure on high terms of the spectra of the alkalis. As Amaldi put it later, “In order to explain the effect that we had found, [Fermi] made the theory of a collision of a very *slow electron* against an atom; and this is exactly the same theory that was used one and a half years later for *slow neutrons* against nuclei,” the experiment that was a stepping-stone to the nuclear age. Another major step was an insight by Lise Meitner and Otto Frisch in late 1938, during a Christmas excursion in the snow while in exile. They knew of George Gamow’s model, which took atomic nuclei to be analogous to liquid drops, and they visualized that a uranium nucleus “drop” could go into such strong oscillations that it would break apart. That is how the awesome possibility of fission was first recognized—though Meitner and Frisch, for decades, were not.

My favorite proof of the usefulness of analogic thinking is found in the work of the nineteenth-century physicist Thomas Young. His fame rests chiefly on his development of the idea that light is a wave phenomenon, which was contrary to the quasi-corpuscular theory of light associated with Newton, widely preferred at that time. In one of his first papers (1800), Thomas Young, at age twenty-seven, writes, “Light is a propagation of an impulse communicated to [the] ether by luminous bodies.” He reminds his reader that “It has already been conjectured by Euler that the colors of light consist of the different frequencies of the vibrations of the luminous ether.” So far this has been only a speculation, and

not one agreeable to the Newtonian-minded establishment of the day. But now, Thomas Young insists instead of conjecture he has *confirmation*: The idea that light is a propagation of an impulse in the ether “is strongly confirmed. . . .” By what? How? “By the analogy between the *colors* of a thin plate and the *sounds* of a series of organ pipes”—two very different things.

Without even stopping to study the details of this surprising and—as it turned out—immensely fruitful analogy between light and sound, we sense the remarkable daring of this transference of meaning. Indeed, the courage of making such a connection seemed so very ill-advised that even when George Peacock, a devoted friend of Young and himself a mathematician and professor at the University of Cambridge, edited and published a collection of Young’s papers in 1855—twenty-six years after Young had died and long after the wave theory had become firmly established—Peacock still felt he must save his readers from some dreadful mistake on this point; so he added an asterisk after Young’s crucial sentence and provided a stern footnote, perhaps unique in the literature: “This analogy is fanciful and altogether unfounded. Note by the Editor.”

Of course, light and sound *are* different. For one thing, Peacock knew that Arago and Fresnel, building on Thomas Young’s work, had determined that light waves are transverse, whereas sound waves in organ pipes are longitudinal. Peacock saw all the differences in the analogy rather than the similarities. But Young’s insight had been a stroke of genius. The colors of a thin plate, or, for that matter, in a soap bubble or a film of oil, depend on the thickness of the layer, just as the sounds made by organ pipes depend on their length; this was the clue that both light and sound, and hence color and pitch, are the result of the properties of waves, specifically interference between waves. Peacock’s editorial comment should have said: By this fruitful analogy, Thomas Young entered eventually into the annals of history, even though a campaign of opposition by the British Newtonians had soon ended his career as a productive scientist.

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Finally, a glance at the third of the tools that can energize the initial phases of research. This aspect is what I call the thematic



Figure 1. *The Immaculate Conception*, Bartolomé Murillo (1617-1682).

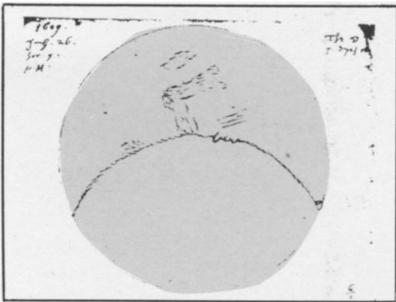


Figure 2. Thomas Harriot's first drawing of the moon, 1609.

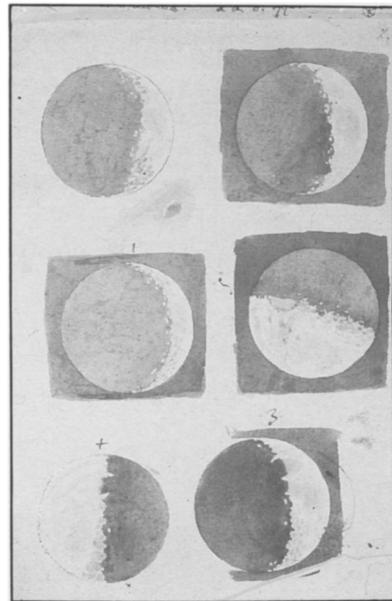


Figure 3. Galileo's ink wash drawings.

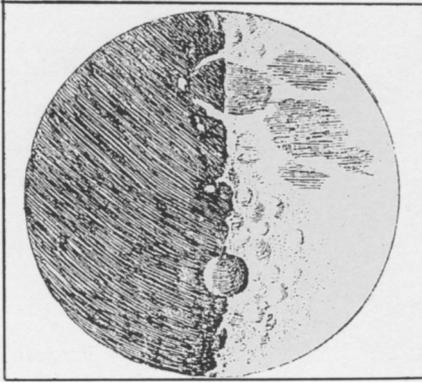


Figure 4. From Galileo's *Sidereus Nuncius* (1610).

Figure 5. Harriot's second lunar drawing, 1610.

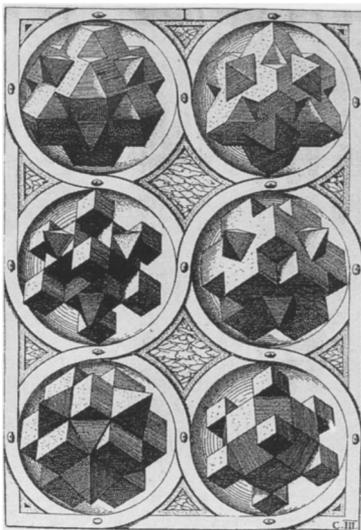
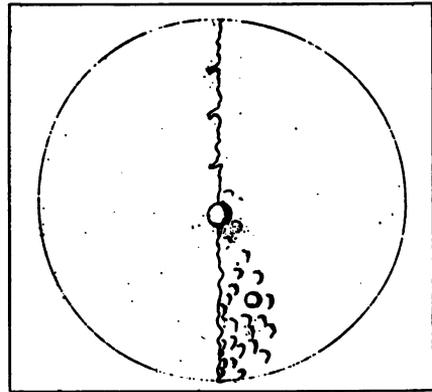


Figure 6. From Wentzel Jamnitzer, *Perspectiva corporum regularum* (1568).



Figure 7. Lodovico Cigoli, *The Virgin of the Immaculate Conception*, 1610-12.

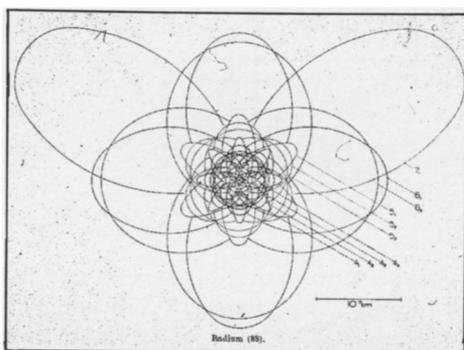


Figure 8. Niels Bohr's representation of the radium atom, prepared for use in his lectures. (From *Die Naturwissenschaften*, 6 July 1923.)

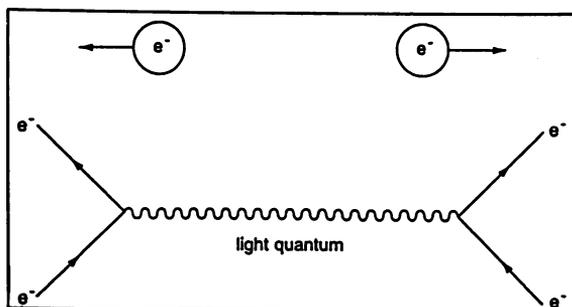


Figure 9. Upper part: the “classical” representation of electrons repelling each other. Lower part: the mutual scattering of the same electrons, represented in space-time and interacting through the exchange of a (virtual) light quantum. (From A. I. Miller, *Imagery in Scientific Thought* [Boston: Birkhäuser, 1984], 257.)

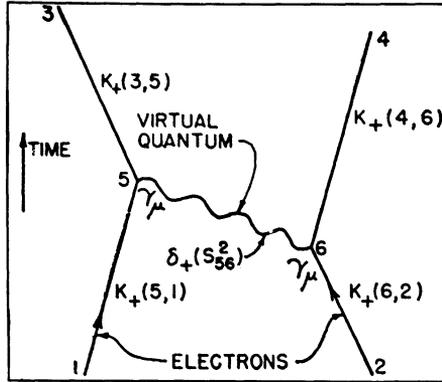


Figure 10. From R. P. Feynman, “Space-Time Approach to Quantum Electrodynamics,” *Physical Review* 76 (1949): 772. Feynman’s caption reads: “The fundamental interaction Eq. (4). Exchange of one quantum between two electrons.” Indeed, the diagram is at least a qualitative visual representation of the scattering of two electrons, a phenomenon properly described by the equation shown in Figure 11.

Hence we have for electrons obeying the Dirac equation,

$$K^{(1)}(3, 4; 1, 2) = -ie^2 \int \int K_{+a}(3, 5) K_{+b}(4, 6) \gamma_{a\mu} \gamma_{b\mu} \times \delta_+(s_{56}^2) K_{+a}(5, 1) K_{+b}(6, 2) d\tau_5 d\tau_6, \quad (4)$$

where  $\gamma_{a\mu}$  and  $\gamma_{b\mu}$  are the Dirac matrices applying to the spinor corresponding to particles  $a$  and  $b$ , respectively (the factor  $\beta_a \beta_b$  being absorbed in the definition, I Eq. (17), of  $K_+$ ).

This is our fundamental equation for electrodynamics. It describes the effect of exchange of one quantum (therefore first order in  $e^2$ ) between two electrons. It

Figure 11. From R. P. Feynman, “Space-Time Approach to Quantum Electrodynamics,” presenting the “Eq. 4” mentioned in Figure 10 that governs the interaction of two electrons.

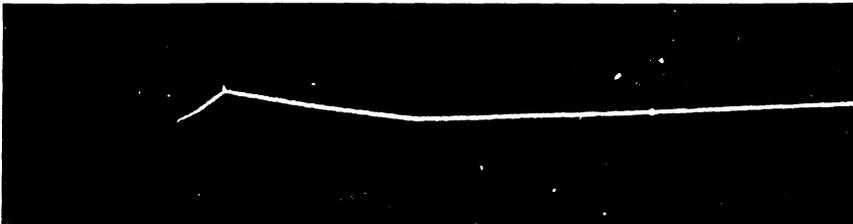


Figure 12. One of C. T. R. Wilson’s earliest cloud chamber photographs indicating the path of an alpha particle and its “abrupt bends.” (From *Proc. Roy. Soc. London* [A] 87 [1912]: 277.)



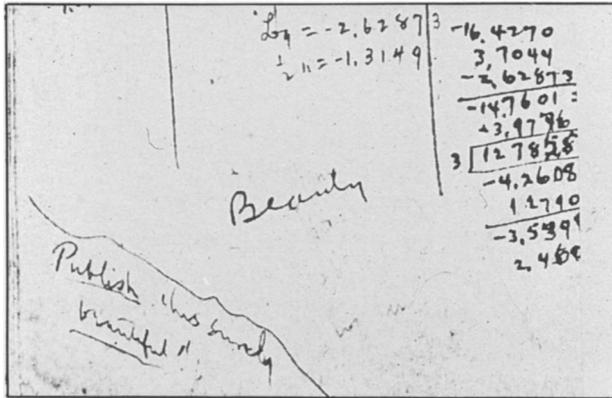


Figure 15. Detail of Figure 14.

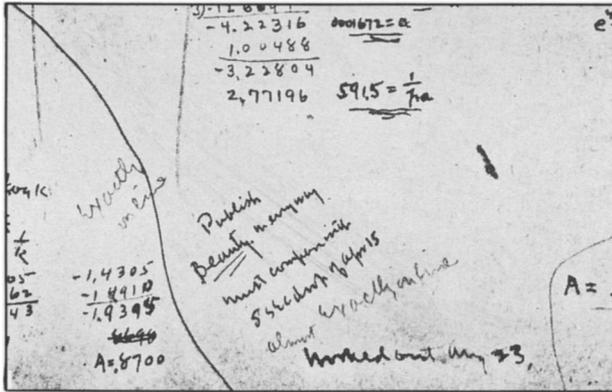


Figure 16.

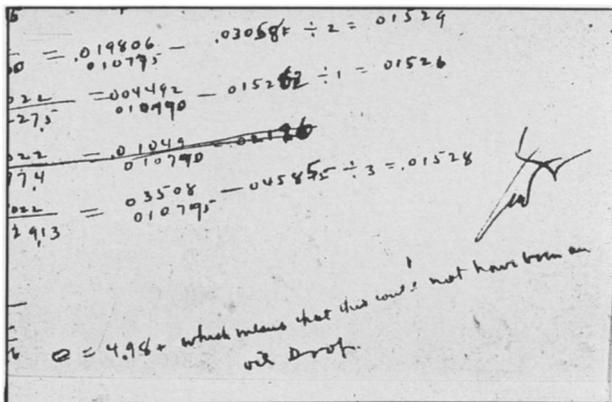


Figure 17. “ $e=4.98+$  [too far off] which means that this could not have been an oil drop.” Millikan had worked with oil drops long enough to be ready to suspect an intruder, e.g., an oil coated dust particle.

imagination. By themata (from the Greek *thema*—that which is laid down by way of a proposition), I mean the often unconfessed or even unconscious basic presuppositions, preferences, and preconceptions that scientists may choose to adopt, even if not led to do so by the data or current theory. This is, of course, a strategy contrary to all good advice, from Francis Bacon's warning against the four Idols, to Karl Popper's insistence on attempting disconfirmation, to today's manuals of proper conduct. And indeed, allegiance to one's themata may well lead to failure, as Darwin's bulldog, T. H. Huxley, warned over a century ago: "Science seems to me to teach in the highest and strongest manner the great truth which is embodied in the Christian conception of entire surrender to the will of God. Sit down before fact as a little child, be prepared to give up every preconceived notion, follow humbly wherever and to whatever abysses nature leads, or you shall learn nothing."

Yet, there are many cases of success where scientists held on to their favorite themata fiercely for a time, even when seemingly contradictory evidence existed initially. We are speaking here of a scientist's willing suspension of disbelief, analogous to that which Samuel Taylor Coleridge identified as the task of the poet, and not far from what John Keats referred to as the "Negative Capability" of great authors (their ability of "remaining content with half-knowledge").

The thematic profile of a scientist emerges when one studies his or her early drafts, laboratory notes, letters, and publications. In the case of Einstein, his unshakable a priori preferences included the following: unification of separate parts of the theories of physics (Steven Weinberg similarly spoke of "Newton's dream to understand all of nature"), invariance, symmetry, completeness of description, and essentially Newtonian causality of events rather than fundamental probabilism (hence his profound disagreement with Niels Bohr's view of physics). Einstein called his presuppositions freely chosen "categories," and in that respect they were different from the categories of Immanuel Kant, which were "unalterable [and] conditioned by the nature of the understanding." Einstein curtly dismissed attacks on his presuppositions with the remark that, for him, thinking without them "would be as impossible as breathing in a vacuum." To be sure, although themata

may motivate and inspire an investigation, eventually they have to stand the test of experience and be judged by the degree to which they contribute to making the world of phenomena more “intelligible.” Nature cannot be fooled. So it may be said that Einstein’s thematic choices served him superbly in the early decades; but during his last years his dogged pursuit of a unified field theory within his presuppositions was hard work on fallow ground.

I have developed the theoretical underpinnings of the concept of themata at length elsewhere, so I shall demonstrate here only two examples of its operational meaning.

At the end of the nineteenth century, physicists could still believe as Newton did that, at their base, nature’s phenomena do not make jumps, that they are not discontinuous. From 1900 on, Planck and Einstein felt it necessary to introduce, though reluctantly, the concepts of quantum jumps of energy at the atomic level and discrete quanta of light energy, later called photons. Whether this “essential discontinuity or rather individuality” of atomic processes, as Bohr called it (1927), was truly necessary became the topic of an unprecedented summit meeting in 1911. The majority of the world’s major physicists assembled in a room in Brussels (at the so-called first Solvay Conference). As it so rarely does, the passionate part of the scientists’ intellectual life came out into the open. Walther Nernst, the organizer of the conference, had said that quantum physics was at bottom “a very odd rule, a grotesque one.” Max Planck wrote afterwards, “For my part, I hate discontinuity. . . .” And Henri Poincaré, upon returning from the Conference, exclaimed: “[Mr. Planck’s is] so strange an hypothesis that every possible means must be sought for escaping it. The search has revealed no escape so far. . . .Is discontinuity destined to reign over the physical universe, and will its triumph be final?” Earlier, he had declared that without the hypothesis of continuity “all science would be impossible.”

Yet discontinuity at the bottom end of the explanatory chain became more irresistible with Ernest Rutherford’s discovery, also in 1911, that the atom, far from being a jelly-like object, harbored a tiny, hard nucleus. Again, exactly three hundred years after 1611, some artists thought the very structure of the universe had been shaken by an earthquake. Thus, the painter Wassily Kandinsky wrote about that period: “The collapse of the atom model was

equivalent, in my soul, to the collapse of the whole world. Suddenly, the thickest walls fell. . . science seemed to me destroyed.” Cultural historians have long puzzled over those uncanny, analogous shifts in sentiment and imagination beyond science, along a variety of fronts, at about that same time. One need only mention the effects of Stravinsky’s ballets (*Firebird* [1910], *Petrouchka* [1911], *Rite of Spring* [1912]), the Armory Show of 1913, and Roger Fry’s post-impressionist exhibit in London of 1910—one cause of Virginia Woolf’s remark, giving a date for the new modernity: “In or about December 1910, human character changed. . . .”

At any rate, most physicists did come to terms rather quickly with nature’s discontinuity among atomic phenomena, in part because in 1912 the British physicist C. T. R. Wilson, by means of dramatic photographs taken with his new invention, the cloud chamber, first presented visible indications of the underlying sub-microscopic events. For example, *Figure 12* (page 198) shows a trail of condensation, a thin line of fog, left along the path of an alpha particle that had streaked out from a bit of radium. As Wilson put it, this trail is “particularly interesting” because of its “two absolutely abrupt bends.” Here is evidence of discontinuity: the alpha particle is sharply deflected after bumping into the heavy nucleus of the gas that is filling the chamber. In fact, the little spur track at the first deflection indicates to the tutored eye the recoil of an unfortunate nucleus after collision.

Such pictures later became the subject of interesting controversy among philosophers about the relation between observables and the underlying reality. But to most scientists, who tend to be pragmatic realists, they were decisive. Robert A. Millikan reported that when these photographs were first shown at a scientific meeting in 1912, they filled its viewers “with amazement and thrill. . . thrill at the complete visibility” of the underlying process. What John Donne might again have called a “new Philosophy” had taken over, riding on its new themata of discontinuity and the disintegration of his “Atomies.” In America, Henry Adams had predicted it all, writing in 1905 in *Education* that the new century would see old unities crumble into multiplicity.

\* \* \*

My second and last example of the thematic component of scientific thought comes from one of my favorite cases, in which the tenacious loyalty to a presupposition is starkly revealed to the historian watching through the keyhole of the laboratory door. During those exciting years around 1911 and 1912, Millikan, a still rather unknown physicist at the very young University of Chicago, decided to measure precisely the charge of the electron—a basic constant of nature whose value was then still much in question. He did not doubt for a moment that all electrons carry the exact same discrete amount of charge (usually symbolized by the letter  $e$ ), just as all atoms of an element were thought to have the same mass. Millikan had long been “quite certain” of this idea chiefly because his personal hero, whom he referred to as “our own Benjamin Franklin,” had stated in 1750 that all electricity had a granular structure, with each granule, as Millikan paraphrased it, consisting of an “electrical particle or atom.”

We shall see in a moment how this idea determined what he did in the privacy of his laboratory, but let it be remembered right now that in the end he did obtain an astonishingly good value for  $e$ , which was cited as part of his Nobel Prize award in 1923. But at the time there was also an alternative to this picture of discreteness. Felix Ehrenhaft of the old University of Vienna, largely influenced by Ernst Mach’s anti-atomism, was convinced that the measured value of  $e$  was only an average, with the actual charges on different electrons varying from extremely small subelectrons to much larger values. And he had his own experimental measurements to prove it (although it turned out later that he was using a method so inadequate as to insure the variability that he was looking for).

Now Millikan found himself in a race between the merits of two contrary themata, not an unusual situation in the history of science. Millikan’s table of data (see *Figure 13*, page 199) from one of his early papers warns us of his willingness to take large risks in the service of an idea, risks at least by our present standards—which we must not be too quick to apply in retrospect. Millikan watched the behavior of charged drops, and he handed out stars to each of the many runs. He explains in the text of the article, “The

observations marked with triple stars are those marked ‘best’ in my notebook.” Double stars are for “very good” ones, singles are “good,” the others only “fair,” and seven observations were “discarded” as being “uncertain.” There are six such tables for the whole series of his experiments at that point, and at the end he gathers them together to find the best value for  $e$ . The use of statistics for data treatment had not yet entered his mind. Yet, the final result,  $e = 4.65 \times 10^{-10}$  esu, was very good for its time and was immediately used by Niels Bohr for his work on the model of the atom. The happy phrase coined by H. C. Oersted, the nineteenth-century physicist, comes to mind: Oersted had said some scientists are capable of an “anticipatory consonance with nature.”

During the next two years, Millikan greatly improved his apparatus for watching the movement of oil drops in electric and gravitational fields. In August 1913, he published his classic and definitive paper. There he gives the data, using experimental runs on fifty-eight separate oil drops, and obtains a value for  $e$  ( $e = 4.774 \times 10^{-10}$  esu, with an uncertainty of one part in a thousand). It could not be improved upon for two decades.

In Millikan’s archives I found his original lab notebooks for this work. We can use them to peep into his laboratory, to see how his thematic predilection—that there exists a unique, discrete value of  $e$ —helped him to select among his data. The fifty-eight experimental runs that he published refer accurately to the corresponding data entries—but they amount to only about 40 percent of the total number of drops he actually examined, leaving unused the other drops recorded in his lab notes. His suspension of disbelief regarding contrary-looking data is clear. Ehrenhaft would probably have been delighted if he had had access to the data in those notebooks that did not make it into Millikan’s publication.

To be sure, every experimenter to this day, particularly when working with newly invented equipment, must have a keen sense about whether external circumstances—in this case voltage fluctuations, temperature changes, turbulences in the chamber—may be interfering with the presuppositions on which the experiment is built. Galileo had analogous problems with his new telescope. Today, our strategies for dealing with discordant data are very different, and in the light of our current, much harsher rules, it is all too tempting in retrospect to accuse Millikan of mischief. That

discussion leads to an important topic, albeit one that is not for today's talk.

Rather, let us acknowledge the enchantment when things go well, which Johannes Kepler could allow himself to share publicly, but which, for better or worse, most scientists have learned to keep out of sight. *Figure 14* (page 199) shows the data and calculations typical for one of the “good” runs; in the lower left-hand corner of the page, Millikan writes: “Beauty. Publish this surely, beautiful!” (See *Figure 15*, page 200.) And, similarly, on page after page, for example in *Figure 16*: “Publish. Beauty in every way. . . Exactly on line almost.”

But in cases where the oil drops are heavy and move too quickly, or where Millikan has other doubts, his euphoria gives way—e.g., “Something wrong,” or “doesn't fit,” or “error high, will not use.” And, indeed, such drops do not make it into the publication (for the most striking example, see *Figure 17*). From Millikan's point of view, they were not even failed runs. They were, in effect, not runs at all. Instead of wasting time trying to puzzle out what caused the difficulty, as he well might have been able to do, he simply went on to the next set of readings with another droplet.

In other people's hands, all this could have ended in disaster. This time, his thematic choice saw him through to success. But on his next research project, on the photoelectric effect, he started out with the wrong presupposition. He worked on it obstinately for ten years, finally giving up reluctantly his beloved presupposition—and it led to the other half of his Nobel Prize award. Yet, without his highly motivating presuppositions, he might not have known how to start or how to persevere in either case.

\* \* \*

The three forms of the private art of scientific imagination that I have described today may help to counter a more common notion of science as a machine-like and passion-free process of induction from undoubtable facts. However, it would also be wrong if one were to neglect the ever-present, complementary set of skills—logical reasoning, craftsmanship, and other disciplined expertise—that must be learned and can be shared. To downplay those would

leave the monuments of our Athens unprotected, to be picked apart by the noisy crows of Sparta.

I conclude on another cautionary note. Of course, we cannot pretend to “explain” a Galileo or a Marie Curie any more than a Dante or a Mozart. Pericles, speaking of the fallen soldiers of the Peloponnesian War, praised them for having laid their deeds “at the feet of their city, as the most glorious contribution they could offer.” So, in their way, did these scientists, some at great personal sacrifice. But *how* mere human minds find an entry into the hidden order of things, how some can open up entirely new worlds and discover hints of the ultimate laws of nature, all this we can only try to illuminate but will never understand fully. On this point, Einstein again has the last word. “Here,” he said, “lies the sense of wonder, which increases ever more—precisely as the development of knowledge itself increases.”

#### SELECTED SOURCES AND FURTHER READING

**On Galileo and the Moon:** Galileo Galilei, *Sidereus Nuncius*, or *The Sidereal Messenger*, translated with an introduction, conclusion, and notes by Albert Van Helden (Chicago, Ill.: University of Chicago Press, 1989). Erwin Panofsky, “Aesthetic Attitude and Scientific Thought,” *Isis* 47 (1956): 3–15. Samuel Y. Edgerton, Jr., “Galileo, Florentine ‘Disegno,’ and the ‘Strange Spottedness’ of the Moon,” *Art Journal* 44 (1984): 225–232. I. Bernard Cohen, “What Galileo Saw: The Experience of Looking through a Telescope,” in Paolo Mazzoldi, ed., *From Galileo’s “Occialino” to Optoelectronics* (Singapore: World Scientific, 1993), 445–472.

**On Thomas Young:** George Peacock, ed., *Miscellaneous Works of the Late Thomas Young* (London: John Murray, 1855). Entry for Thomas Young (by Edgar W. Morse) in C. C. Gillispie, ed., *The Dictionary of Scientific Biography* 16 (1976): 562–572. Henry Steffens, *The Development of Newtonian Optics in England* (New York: Science History Publications, 1977).

**On Robert A. Millikan:** Robert A. Millikan, *The Electron*, edited with an introduction by Jesse W. M. Du Mond (Chicago, Ill.: University of Chicago Press, rev. ed., 1963). [R. A. Millikan], *The Autobiography of Robert A. Millikan* (New York: Prentice Hall, 1950). Gerald Holton, *The Scientific Imagination: Case Studies* (New York: Cambridge University Press, 1978), chap. 2.

**On Albert Einstein and the Use of Themata:** Albert Einstein, *Ideas and Opinions* (New York: Crown Publishers, 1982). In Paul Arthur Schilpp, ed., *Albert Einstein: Philosopher-Scientist* (Evanston, Ill.: The Library of Living Philosophers, Inc., 1949), “Autobiographical Notes” by Einstein, 2–95. In this essay I

have also drawn on portions of three of my books: *Thematic Origins of Scientific Thought: Kepler to Einstein* (Cambridge, Mass.: Harvard University Press, rev. ed., 1988), chaps. 6–9; *The Advancement of Science, and its Burdens* (New York: Cambridge University Press, 1986), chaps. 3–4; and *Einstein, History, and Other Passions* (New York: American Institute of Physics Press, 1995), chaps. 2, 8.

**On Feynman and Visualization:** Silvan S. Schweber, *QED and the Men who Made It: Dyson, Feynman, Schwinger, and Tomonaga* (Princeton, N.J.: Princeton University Press, 1994), chap. 8. Arthur I. Miller, *Imagery in Scientific Thought: Creating 20th Century Physics* (Boston, Mass.: Birkhäuser, 1984), chaps. 4, 6. On Werner Heisenberg's earlier work, two of his books are easily accessible: *Physics and Philosophy: The Revolution in Modern Science* (New York: Harper and Brothers Publishers, 1958), and *Physics and Beyond: Encounters and Conversations* (New York: Harper and Row, 1971). On the modern context of physics, see Steven Weinberg, *Dreams of a Final Theory* (New York: Pantheon Books, 1992; New York: Vintage Books, 1994).