Understanding Scientific Reasoning
Second Edition

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Analog Models

Scientists often talk about models when in the process of developing a new theory. The kind of situation in which this occurs has the following general characteristics. There is some type of system that is not yet very well understood. In order to develop a theory of such a system, scientists speculate that it may be like some other kind of system that is well understood. That is, they conjecture that the unknown systems might have some similarities of structure with the known systems. They then proceed to develop a theory of the new systems based on their understanding of the similarities that might exist. This sort of reasoning is often called reasoning by analogy. It is based on the known or suspected analogies between two sorts of systems. I will refer to the known system as an analog model of the unknown system.

The use of analog models in science is neatly illustrated by early attempts (around 1900) to develop a theory of atoms. From the then recent discovery of X-rays, radioactivity, and other phenomena, it was clear that atoms contained both positive and negative electric charges. The problem was to figure out how these charges were arranged in an atom in such a way that would explain how atoms could exist as stable entities and not simply collapse or fly apart.

One of the first attempts to describe the actual structure of atoms was based on a raisin-pudding model of the atom. J. J. Thomson is said to have suggested that the positive charge is spread out like pudding and that the electrons move around like raisins when the pudding is disturbed. Later experiments by Ernest Rutherford seemed to show that the positive charge was not spread out, but highly concentrated. Rutherford and later Niels Bohr proposed a different model. They suggested that we think of the atom as being analogous to the solar system. An atom, they said, is like a miniature solar system. All the positive charge is in the center, just as the sun is in the center of the solar system. The negative charge is carried by electrons, which move around the center like planets in orbit. So Rutherford and Bohr were taking the solar system as an analog model for the atom. They said that the structure of an atom is analogous to the structure of the solar system.

There is no doubt that the analogy between the solar system and atoms was extraordinarily fruitful. It suggested all sorts of questions which formed the basis of much research. For example, “How fast are the electrons moving around in their orbits?” “Are the orbits circular or elliptical?” In investigating such questions, scientists learned much about atoms. In particular, they learned about many respects in which atoms are not like the solar system. So, in the end, a good analogy leads to its own revision.

It is clear, then, that analog models play an important role in scientific research—particularly in the creation and development of new theories. The question for us, however, is whether analogies play any role in the justification of the new theory. For example, does the analogy with the solar system provide any justification for Bohr’s theory of the atom? We are not trying to learn how scientists reason in the creative process of developing...
Reasoning about Theories

a new theory. We seek only to be able to evaluate the arguments used to justify theories after they have been developed.

This is again a matter of debate among philosophers of science. The safe answer is No. There is no really good account of inductive arguments that are based on analogies, although several have been proposed. There is, however, a good account of how to justify theories themselves. So we shall say that each theory must stand on its own. However useful some model may have been in creating the theory, and however well justified our hypotheses about the model itself, any new theory must be justified by information about its own subject matter. You cannot justify hypotheses about atoms on the basis of data about the solar system.
Mental Leaps
Analogy in Creative Thought

Keith J. Holyoak and Paul Thagard

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tively than more prosaic admonishments would have. In chapter 9 we
will discuss other analogies that are important in several Asian cultures.

Philosophers are not the only thinkers who use analogies in trying
to gain a systematic understanding of the world. In the next chapter we
describe analogies that have made noteworthy contributions to science
and technology.

Summary

We have seen that analogies have played an important role in several of
the central branches of philosophy: metaphysics (God, other minds),
epistemology (Plato's cave, Neurath's ship), and ethics. (The develop-
ment of theories in logic has also employed analogy; George Boole
explicitly modeled his early work in propositional logic on algebra, and
so did Charles Peirce.) Analogies have contributed to religious and
philosophical thought in India and China as well as in Europe and
America.

Just as evaluation of analogies in decision making is in part a matter
of deliberative coherence, so evaluation of analogies in explanation is in
part a matter of explanatory coherence. The most powerful analogies are
ones based on system mappings with higher-order relations, such as
"explain" and "cause," which afford the analogies a structure that di-
rectly contributes to their explanatory purposes. Like decision making,
explanation can benefit from use of multiple analogies; and evaluation
of competing analogies is part of the process of evaluating competing
hypotheses.

Great Scientific Analogies

Several years after he carried out his famous kite experiment, Benjamin
Franklin responded to a query concerning how he came to propose it,
by quoting from a journal that he had kept at the time:

Nov. 7, 1749. Electrical fluid agrees with lightning in these particulars: 1. Giving
light. 2. Color of the light. 3. Crooked direction. 4. Swift motion. 5. Being
conducted by metals. 6. Crack or noise in exploding. 7. Subsisting in water or
ice. 8. Reeding bodies it passes through. 9. Destroying animals. 10. Melting
metals. 11. Firing inflammable substances. 12. Sulphureous smell. —The electric
fluid is attracted by points. —We do not know whether this property is in
lightning. —But since they agree in all the particulars wherein we can already
compare them, is it not probable they agree likewise in this? Let the experiment
be made.

The kite experiment was thus inspired by the analogy Franklin noticed
between lightning and electrical phenomena, such as sparks.

Historians, philosophers, and psychologists of science have docu-
mented many instances of analogical thinking. This chapter presents a
collection of many of the most important analogies that scientists have
used, and it provides an account of the main mechanisms required for
analogical thinking in science. The various contributions of analogy to
the discovery, development, and evaluation of scientific theories have
involved a number of different ways of representing, constructing, and
using analogies. Analogies are also important in teaching science, as well
as other topics. We draw some conclusions concerning the educational
use and misuse of analogies.

It would be easy to compile a list of hundreds of analogies that have
been used by scientists, but our goal is to identify the analogies that
qualify as most important according to two criteria. First, the analogy
must have clearly contributed to some vital stage of a scientist's thinking, whether it was the discovery or development of an idea or the later argumentation in its defense. Second, the scientist's thinking that involved the analogy must have contributed to a major theoretical advance. The theory to which the analogy contributed need not be accepted today, but it must have been important in its own time and context.

Because additional candidates may well be defensible, the following list is not definitive. However, it suffices to provide a broad sample of highly significant analogies for analysis and generalization, presented here in chronological order. As we saw in the last chapter, rich analogies abound in the writings of Plato, Aristotle, and other Greek thinkers. But we have identified only one scientific analogy of enduring significance before the modern era.

1. Sound/water waves The analogy between sound and water waves was discussed in chapter 1. Water waves were first used to suggest the nature of sound by the Greek Stoic Chrysippus around the second century B.C., but our knowledge of his views is fragmentary. In the first century A.D., the Roman architect Vitruvius, in the course of explaining the acoustic properties of Greek amphitheaters, explicitly compared the sound of voices to water waves that can flow out and bounce back when obstructed, just as sound spreads and echoes. Here we have the ancient origins of the modern wave theory of sound.

2. Earth/small magnet In his landmark work De Magnete, published in 1600, William Gilbert described important experimental investigations of the nature of magnets, and he proposed for the first time that the planet earth is a giant magnet. The basis for his hypothesis was a systematic comparison between the properties of the earth, such as how it attracts compasses, and the properties of the small spherical magnets on which he had performed many experiments. The earth is like these objects in many respects, so, according to Gilbert, we should infer that the earth acts like a magnet, engendering the magnetism of the objects that were part of it. Indeed, since the common properties of the earth and small magnets define what it means to be a magnet, the earth not only acts like a magnet, it is a magnet.

3. Earth/moon Galileo's Dialogue concerning the Two Chief World Systems, published in 1630, contained two analogies that made important contributions to his contention that the earth moves. First, Galileo compared the earth to the moon, both of which are spherical, dark, opaque, dense, and solid, with similar expanses of light and dark and of land and sea. Since the moon was known to move in an orbit, he argued it was reasonable to suppose that the earth does too.

4. Earth/ship Galileo used a different analogy to rebut an argument that the earth does not move. Opponents of his theory argued that if a rock is dropped from a tower, it lands at the base of the tower, suggesting that the tower, and hence the earth, is not in motion. Galileo countered this argument with a ship analogy, comparing the tower to the mast of a ship that is moving. He pointed out that a rock dropped from the top of the mast will fall and land at the base of the mast even though the ship is moving.

5. Light/sound In his 1678 Treatise on Light, Christian Huygens used an analogy between light and sound in support of his wave theory of light. That theory was eclipsed for more than a century by Newton's particle theory but was revived in the early nineteenth century by Thomas Young and Augustin Fresnel. These scientists exploited the analogy between light and sound to develop and defend a wave theory of light.

6. Planet/projectile Toward the end of his celebrated Principia (1687), Isaac Newton used an analogy to help bring planetary motion within the scope of his theory of gravitation. He compared a planet to a stone thrown upward from the earth with greater and greater force. He presented a diagram to show how with a great enough force the path of the stone would become the path of an object in orbit around the earth. Newton used this analogy to support his hypothesis that the orbits of the planets are governed by gravitational force.

7. Lightning/electricity We have already described Benjamin Franklin's famous analogy leading to the hypothesis that lightning was a form of electricity. Like the earth/small magnet example, this comparison became more than an analogy. Following Franklin's work, the definition of electricity has expanded to include the natural phenomenon of lightning.

8. Respiration/combustion During the 1770s when Antoine Lavoisier was developing his oxygen theory of combustion, he also developed a theory of the role of oxygen in animal respiration. Much of his thinking was guided by an analogy between respiration and combustion, both of which involve a change of oxygen into carbon dioxide and a provision of heat.

9. Heat/water In 1824, Nicholas Leonard Sadi Carnot provided a thorough discussion of the motive power of heat, drawing heavily on an analogy between heat and waterfalls. He argued that heat acts on substances, just as water acts on waterfalls, with the power depending in the former case on the amount of calorific (heat substance) and in the latter on the height of the waterfall. The idea of heat as a fluid was already well established by this time, but Carnot put it to much more systematic use.

10. Animal and plant competition/human population growth Charles Darwin reported that he arrived at the basic idea of natural selection in 1838 by fortuitous reading of Malthus's tract on human population growth. Darwin had been searching for a mechanism that could produce the evolution of species, and he realized from Malthus that rapid population growth in the face of limited food and land could lead to a struggle for existence. Darwin noticed the analogy between potential human strife (produced by population growth's outstripping resources) and competition among animals and plants for survival.

11. Natural selection/artificial selection A different analogy played a much greater role in the development and evaluation of Darwin's theory of evolution by natural selection. He often compared natural selection to the artificial selection performed by breeders, who exploited the inherent variability in animals
and plants to choose desired features. Natural selection leads to different species, Darwin argued, just as artificial selection leads to different breeds. Darwin used this analogy in the *Origin of Species* (1859) and elsewhere, both in developing explanations and in arguing for the acceptability of his overall theory.

12. **Electromagnetic forces/continuum mechanics** James Clerk Maxwell was explicit and enthusiastic about the use of mechanical and mathematical analogies. The most important application in his own thinking was the construction in the 1860s of a Diagrammatic mechanical model for electrical and mechanical forces, consisting of a fluid medium with vortices and stresses. He was able to abstract from this mechanical analog a general mathematical description that could be applied directly to electromagnetism.

13. **Benzene/snake** As we mentioned in chapter 1, Friedrich Kekulé proposed in 1865 a new theory of the molecular structure of benzene. According to Kekulé, he was led to the hypothesis that the carbon atoms in benzene are arranged in a ring by a reverie in which he saw a snake biting its own tail. This example, like those of Maxwell, Newton, and Morgan, illustrates how visual representations can contribute to creative thinking using analogy.

14. **Chromosome/beaded string** In 1915, Thomas Morgan and his colleagues explained complex phenomena of inheritance by comparing chromosomes to a string containing beads corresponding to the various factors leading to inheritance. Within a few years, those factors had come to be called "genes." The beaded-string analogy was most useful for describing how novel linkages could arise from crossover of chromosomes, just as new patterns of beads could arise from breaking and recombining the string.

15. **Bacterial mutation/slot machine** In 1943, Salvador Luria was trying to find experimental support for his view that phage-resistant cultures of bacteria arise because of gene mutations, not because of action of the phage on the bacteria. (A phage is a viral organism that destroys bacteria.) None of his experiments worked, but at a faculty dance at Indiana University he happened to watch a colleague putting dimes into a slot machine. He realized that slot machines pay out money in a very uneven distribution, with most trials yielding nothing, some yielding small amounts, and rare trials providing jackpots. He then reasoned that if bacteria become resistant because of gene mutations, then the numbers of resistant bacteria in different bacterial cultures should vary like the expected returns from different kinds of slot machines. This reasoning led to an experiment and theoretical model, for which he was awarded a Nobel prize.

16. **Mind/computer** Numerous analogies have been used over the centuries in attempts to understand the nature of mind and thinking. By far the most fertile has been the use since the 1950s, by Alan Turing and many others, of comparisons between thinking and computation. Computational ideas have suggested hypotheses about the nature of mind that have led to much psychological and computational experimentation. As we will discuss below, this analogy is very dynamic and complex; ideas about computation have influenced conceptions of the mind, which have in turn had an impact on the evolution of new types of computers.

Notably absent from this list are two well-known analogies that have often been used in teaching. Molecules of gases are often compared to billiard balls in motion, but we have not been able to find any use of this analogy by the developers of the kinetic theory of gases. Another famous analogy is the comparison of the Rutherford-Bohr model of the atom with the solar system, but the analogy does not seem to have played a role in the creation of their model.

These examples of scientific analogies vary along several important dimensions. Let us look in particular at the purposes served by the analogies and at the cognitive mechanisms involved in their construction and application.

**Purposes**

Scientific analogies have at least four distinguishable uses: discovery, development, evaluation, and exposition. The most exciting is discovery, when analogy contributes to the formation of a new hypothesis. After a hypothesis has been invented, analogy may contribute to its further theoretical or experimental development. In addition, analogy can play a role in the evaluation of a hypothesis, as revealed in the arguments given for or against its acceptance. Finally, analogies are often used in the exposition of science, when new ideas are conveyed to other people by comparing them with old ones. We shall see that an analogy can have more than one use.

Of the uses of analogy, discovery is the hardest to document, since records are far less frequently kept of the very beginnings of hypotheses than of their development and evaluation. Nevertheless, three of the above analogies can clearly be seen as contributing to discoveries: Darwin's animal and plant competition/human population growth, Maxwell's electromagnetic forces/continuum mechanics, and Kekulé's benzene/snake. The cognitive mechanisms for producing the discoveries were quite different in these cases, as we will see in the next section, but all the analogies played a crucial role in forming the hypotheses that were developed.

We can conjecture that several other analogies may have played a role in discovery. Chrysippus may well have been inspired to conjecture that sound moves in waves, by noticing water waves and forming the sound/water wave analogy. And perhaps Franklin derived not only the idea for his experiment but also the basic hypothesis that lightning is electricity by grasping the lightning/electricity analogy. The famous
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Science and the Human Spirit

ALAN LIGHTMAN

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their thoughts so as to gain as ordered and structured an understanding as possible.

But in fiction, a topic sentence is usually fatal. Because the power of fiction is emotional and sensual. You want your reader to feel what you’re saying, to smell it and hear it, to be part of the scene you are creating. You want your reader to be blindsided, to let go and be carried off to a magical place. Every reader will travel differently, depending on his or her own experiences of life. With a topic sentence, you don’t leave room for your reader’s own imagination and creativity. The difference can be stated in terms of the body. In expository writing, you want to go first to your reader’s brain. In creative writing, you want to bypass the brain and go straight for the stomach, or the heart.

(2001)

Please note: Lightman’s use of the term ‘metaphor’ is synonymous with ‘analogies’.

METAPHOR IN SCIENCE

I REMEMBER THE DAY, during my first course in cosmology, when the professor was trying to explain how the universe could be expanding outward in all directions, but without any center of the expansion. To his credit, the teacher had covered the blackboard with equations, but we students still couldn’t picture the situation. How could something explode uniformly in all directions without a middle of the explosion? Then, the professor said to pretend that space is two-dimensional and that the stars and galaxies are dots on the surface of an expanding balloon. From the point of view of any one dot, the other dots are moving away from it in all directions, yet no dot is the center. This powerful metaphor, first introduced by Arthur Eddington in 1931, has helped students of cosmology ever since, in every country and every language where the subject is taught. It works for anyone who has seen a balloon inflated.

Metaphor is critical to science. Metaphor in science serves not just as a pedagogical device, like the cosmic
balloon, but also as an aid to scientific discovery. In doing science, even though words and equations are used with the intention of having precise meanings (as I have discussed in my essay “Words”), it is almost impossible not to reason by physical analogy, not to form mental pictures, not to imagine balls bouncing and pendulums swinging. Metaphor is part of the process of science. I will illustrate this point with some examples from physics.

In an essay on light and color in 1672, published in Philosophical Transactions of the Royal Society, Isaac Newton describes his first experiments with a prism. He darkened his chamber, made a small hole in his “window-shuts,” and let a ray of sunlight enter a prism and spread out into colors on the opposite wall. He then interprets this phenomenon in terms of a theory of light:

Then I began to suspect whether the rays, after their trajectory through the prism, did not move in curved lines, and according to their more or less curvity tend to divers parts of the wall. And it increased my suspicion, when I remembered that I had often seen a tennis ball struck with an oblique racket describe such a curved line. . . . For the same reason, if the rays of light should possibly be globular bodies, and by their oblique passage out of one medium into another,

acquire a circulating motion, they ought to feel the greater resistance from the ambient ether on that side where the motions conspire, and hence be continually bowed to the other.

This passage is particularly revealing because it is a diary of Newton’s personal thoughts in trying to understand the nature of light. Although Newton subsequently rejected the idea that light rays can curve through space, he continued to develop his corpuscular theory of light. In Query 29 of the Opticks (1704), Newton writes that rays of light are “bodies of different sizes, the least of which may take violet, the weakest and darkest of the colours and the most easily diverted by refracting surfaces.” The largest and strongest light corpuscles carry red, the color least bent by a prism. Newton’s mechanical worldview, of which light was only a part, held sway for two centuries.

A hundred years after Newton’s Opticks, the physician and physicist Thomas Young allowed sunlight from his window to fall on a screen with two small holes in it. He then observed the alternating pattern of light and dark striking the opposite wall. From these patterns, Young proposed, in a paper entitled “Interference of Light” (1807), that light consisted of “waves” rather than particles:
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Supposing the light of any given colour to consist of undulations of a given breadth, or of a given frequency, it follows that these undulations must be liable to those effects which we have already examined in the case of the waves of water, and the pulses of sound.

Young goes on to describe clearly the interference of two sets of circular waves moving outward from the two holes in his screen—a process of positive and negative reinforcement that would produce just the pattern of light seen on the wall. One cannot imagine how Young would have interpreted his observations without having seen overlapping ripples in a pond.

The great nineteenth-century physicist James Clerk Maxwell used an elaborate mechanical model, actually a sustained metaphor, to fathom the workings of electricity and magnetism. By analogy with fluids, Maxwell envisioned a magnetic field to be made out of closely spaced little whirlpools, which he called vortices. To solve the problem of what happens when two of these neighboring whirlpools touch and try to slow each other down, Maxwell mentally inserted between each pair of vortices a system of electric particles that would act as ball bearings. Designed for the purpose of reducing friction, the electric particles were also responsible for carrying electric current. The mechanical metaphors here are striking. In his paper “On Physical Lines of Force” (1861), Maxwell notes:

In mechanism, when two wheels are intended to revolve in the same direction, a wheel is placed between them so as to be in gear with both, and this wheel is called an “idle wheel.” The hypothesis about the vortices which I have to suggest is that a layer of particles, acting as idle wheels, is interposed between each vortex.

Maxwell’s most celebrated contribution to the theory of electricity and magnetism was the prediction of oscillating waves of electric and magnetic forces, called electromagnetic waves, which travel through space at the speed of light. These waves were theoretically discovered by Maxwell after he added a single new mathematical term, called the “displacement current,” to the equations of electricity and magnetism previously worked out by others. How did Maxwell deduce his hypothetical displacement current? When I first learned the theory of electricity and magnetism as a college physics major, I thought that the displacement current had been derived by requiring mathematical consistency and the conservation of electric charge. But, in fact, Maxwell was motivated by the demands of his mechanical model. He knew from experiments that an electric or
magnetic field can store energy. Because Maxwell had a mechanical picture of his subject, and a mechanical view of the world, such energy could only be mechanical in nature. Maxwell therefore proposed that electrical and magnetic energy was stored by stretching, or displacing an elastic medium that filled up space, just as energy is stored in a stretched rubber band. In his classic paper of 1865, “A Dynamical Theory of the Electromagnetic Field,” published in the Royal Society Transactions, Maxwell writes:

Electric displacement, according to our theory, is a kind of elastic yielding to the action of the force, similar to that which takes place in structures and machines owing to the want of perfect rigidity of the connexions. . . . Energy may be stored in the field . . . by the action of electromotive force in producing electric displacement. . . . [I]t resides in the space surrounding the electrified and magnetic bodies . . . as the motion and strain of one and the same medium.

When an electric force oscillated in time, the electric particles in the elastic medium oscillated in response, giving rise to the so-called displacement current. The underlying elastic medium that allowed all of this to happen was called “ether.” The ether was the material substance through which electromagnetic waves propagated, just as air is the substance through which sound waves propagate, by bumping one air molecule into the next. Again, in Maxwell’s words, “We have therefore some reason to believe, from the phenomena of light and heat, that there is an aethereal medium filling space and permeating bodies, capable of being set in motion and of transmitting that motion from one part to another.” Maxwell’s mechanical model for electricity and magnetism, including the ether, was completely fictitious, but it led him to the correct equations.

In 1931, the Belgian priest and physicist Georges Lemaître published a stunning model for the origin of the universe. It was already known at this time—both from Lemaître’s own theoretical work and from contemporary telescopic observations—that the universe is evolving. It was also known that very energetic particles, called cosmic rays, were constantly bombarding Earth from outer space, although the nature and origin of these particles was still a mystery. Lemaître proposed that cosmic rays originated billions of years ago from the radioactive disintegrations of enormous atoms and had been traveling through space ever since. Each of these ancient, massive atoms, in fact, was the parent of a star. Going back still further in time, when the cosmos was smaller and denser, the universe itself began as a single, giant atom, whose gradual disintegrations into smaller and smaller pieces formed nebulae, stars, and

We can conceive of space beginning with the primeval atom and the beginning of space being marked by the beginning of time. The first stages . . . consisted of a rapid expansion determined by the mass of the initial atom. . . . The atom-world was broken into fragments, each fragment into still smaller pieces. . . . The evolution of the world can be compared to a display of fireworks that has just ended.

In this example, both the literal and the metaphorical pieces of the metaphor arise from the unseen world of physics. Lemaître has been called the father of the Big Bang model of cosmology, but his primeval atom hypothesis went far beyond any theoretical or observational evidence.

The above examples should not be taken to mean that only the most brilliant scientists—the Newtons and the Maxwells—use metaphor in their work. Metaphor and analogy are rampant in physics. A graduate student and I recently calculated how gamma rays “reflect” from a layer of cold gas. In a discussion of this problem at the blackboard, beneath the equations, we drew a picture of a wavy line moving toward a wall. The line represented a single “particle” of light, called a photon, and the wall was the surface of the medium of gas. The conversation went something like this: “A high-energy photon penetrates very deeply into the medium before it first scatters off an electron. Then the photon scatters several more times, bouncing around, losing energy, and finally works its way back up to the surface of the medium, where it escapes.”

I will end with an example from the forefront of theoretical physics—the string theory. The concept of strings has emerged from highly mathematical and formal attempts to describe the fundamental forces of nature. According to current string theory, the smallest unit of matter is not a pointlike object, but a one-dimensional structure called a “string.” Here are some descriptions that leading string theorists have had the courage to put into print. “Scattering of strings is described by the simple picture of strings breaking and joining at the end.” “Since a string has tension, it can vibrate much like an ordinary violin string. . . . In quantum mechanics, waves and particles are dual aspects of the same phenomenon, and so each vibrational mode corresponds to a particle.”

Ultimately, we are forced to understand all scientific discoveries in terms of the items from daily life—spinning balls, waves in water, pendulums, weights on springs. We have no other choice. We cannot avoid
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forming mental pictures when we try to grasp the meaning of our equations, and how can we picture what we have not seen? As Einstein said in *The Meaning of Relativity*, “The universe of ideas is just as little independent of the nature of our experiences as clothes are of the form of the human body.”

Sometimes different pictures of the same problem provide new insights. For example, the path that the Earth takes in orbiting the sun can be described either as a distant response to the sun itself, ninety-three million miles away, or as a local response to a gravitational field, filling or warping space around the sun. These two descriptions are mathematically equivalent, but they bring to mind very different pictures. As Richard Feynman comments in *The Character of Physical Law* (1965), they are equivalent scientifically but very different “psychologically,” especially when we are trying to guess new laws of nature. In one picture, we focus on the two masses; in the other, on the space between them.

Physicists have a most ambivalent relationship with metaphor. We desperately want an intuitive sense of our subject, but we have also been trained not to trust too much in our intuition. We like the sturdy feel of the Earth under our feet, but we have been informed by our instruments that the planet is flying through space at a hundred thousand miles per hour. We find comfort in visualizing an electron as a tiny ball, but we have also been shocked to discover that a single electron can spread out in ripples, like a water wave, occupying several places at once. We crave the certainty of our equations, but we must give names to the symbols. At the age of twenty-five, Maxwell reflected on both the service and the danger of physical analogy in a paper entitled “On Faraday’s Lines of Force” (1856), published in the *Transactions of the Cambridge Philosophical Society*:

The first process therefore in the effectual study of science, must be one of simplification and reduction of the results . . . to a form in which the mind can grasp them . . . We must, therefore, discover some method of investigation which allows the mind at every step to lay hold of a clear physical conception, without being committed to any theory founded on the physical science from which that conception is borrowed.

When the quantum theory was being developed, in the first two decades of this century, physicists agonized over their inability to picture the wave-particle split personality of subatomic particles. In fact, physicists violently disagreed over whether such pictures were even useful. In 1913, Niels Bohr, a pioneer of quantum theory, proposed a model for the atom in which electrons orbited about a central nucleus. Max Born
commented a decade later (Die Naturwissenschaften, vol. 27) that “a remarkable and alluring result of Bohr’s atomic theory is the demonstration that the atom is a small planetary system . . . the thought that the laws of the macrocosmos in the small reflect the terrestrial world obviously exercises a great magic on mankind’s mind.” Referring to this same Bohr model, Werner Heisenberg warned that “quantum mechanics has above all to free itself from these intuitive pictures . . . that in principle [are] not testable and thereby could lead to internal contradictions” (Die Naturwissenschaften, vol. 14).

In the 1920s and 1930s, there were two competing formulations of quantum theory, eventually shown to be mathematically equivalent. Heisenberg was the architect of the highly abstract version; Erwin Schrödinger had worked out a more visual theory. In a letter to Wolfgang Pauli in 1926, Heisenberg wrote, “The more I reflect on the physical portion of Schrödinger’s theory the more disgusting I find it.”

Schrödinger, in his reply in the Annalen der Physik, wrote that he felt “repelled by the methods of transcendental algebra” in Heisenberg’s theory, “which appeared very difficult” and had a “lack of visualizability.” A few years later, in 1932, Professor Heisenberg ascribed the nuclear force between a proton and a neutron to the “migration” (Platzwechsel) of an electron between them. Where did the alphas and betas in Heisenberg’s matrices or the readings from the electrometers say that an electron could migrate? Remarkably, Heisenberg’s image of migrating particles as agents of force led three years later to Hideki Yukawa’s successful prediction of a new elementary particle, the meson.

Ultimately, Bohr himself was frustrated in his attempts to grasp intuitively the world of the atom. In 1928, he lamented (Nature Supplement, April 14, 1928):

We find ourselves here on the very path taken by Einstein of adapting our modes of perception borrowed from the sensations to the gradually deepening knowledge of the laws of nature. The hindrances met with on this path originate above all in the fact that . . . every word in the language refers to our ordinary perceptions.

Many contemporary physicists have essentially given up trying to describe the fundamental elements of nature by anything based on common sense. Richard Feynman has remarked that he can picture invisible angels but not light waves. Steven Weinberg, like Bishop Berkeley, seems on the brink of abandoning the material world altogether when he says that after you have described how an elementary particle behaves under various mathematical operations, “then you’ve said everything there
is to say about the particle . . . the particle is nothing else but a representation of its symmetry group" (R. Crease and C. Mann, The Second Creation: Makers of Revolution in Twentieth-Century Physics, 1986). Yet physicists still use metaphors. Cosmologists still discuss how the universe “expanded and cooled” during the first nanosecond after its birth. Relativists still talk about the “semipermeable membrane” around a black hole. String theorists still describe their unseen subatomic strings as “stretching, vibrating, breaking.” What other choice do we have? We must breathe, even in thin air.

But there is a difference between metaphors used inside and outside of science. In every metaphor, there is a principal and a subsidiary object, the literal and the metaphorical, the original and the model. When we use metaphors in ordinary human affairs, we usually have a good sense of the principal object to begin with. The metaphor deepens our insight. When we hear that “the chairman plowed through the discussion,” we already know a good deal about chairmen, committees, and tiring discussion. But when we say that a photon scattered off an electron, what concrete experience do we have with electrons or photons? When we say that the universe is shaped like the surface of a balloon, what do we really know about how space curves in three dimensions?

Galileo admired Copernicus for being able to imagine that the Earth moved, against all common sense. But at least Copernicus understood that the Earth was a ball and had seen other balls move. The objects of physics today, by contrast, are principally known as runes in equations or blips from our instruments. Earlier physicists had an immediate and tactile relation to their subjects. Descartes could see the disjointed image of a pen half in water and half in air. Du Fay could rub cats’ fur against copal or gum-lack or silk. Count Rumford could feel the heat in a cannon just bored. But in the last century or so, science has changed. Physics has galloped off into territories where our bodies cannot follow. We have built enormous machines to dissect the insides of atoms. We have erected telescopes that peer out to unimaginable distances. We have designed cameras that see colors invisible to human eyes. Theorists have worked out equations to describe the beginning of time. The objects of physics today are far removed from human sensory experience.

As a result, it seems to me that metaphors in modern science carry a greater burden than metaphors in literature or history or art. Metaphors in modern science must do more than color their principal objects; they must build their reality from scratch. Such substance, in the palm of a modern physicist, is often hard to let go of. Although aware that the ether was based only on mechanical analogy, Maxwell believed it existed. The
year before he died, Maxwell wrote in the ninth edition of *The Encyclopaedia Britannica* (1878) that he had “no doubt that the interplanetary . . . spaces are not empty but are occupied by a material substance or body, which is certainly the largest . . . body of which we have any knowledge.” If a giant of science like Maxwell was seduced by his own metaphor, what can happen to the rest of us? We ought not to forget that when physicists say a photon scattered from an electron, they are discussing that which cannot be discussed. We can see the tracks in a cloud chamber, but we cannot see an electron. Metaphors in science—although a critical part of our reasoning and discovery—should be handled with caution, and with a clear knowledge of the limits of our sensory experience of the world. We are blind people, imagining what we don’t see.

(1988)

**INVENTIONS OF THE MIND**

MATHEMATICS, FOR ME, has always been a means to an end. Like many other scientists, I have some facility with math. But I found from a young age that I could not become passionate about a problem unless it had physical meaning. How did a radio work? Why did a spoon halfway in water appear to bend sharply in two? Why was upstairs usually warmer than downstairs? Growing up, I stocked a closet off my room with capacitors and resistors, wire and batteries, test tubes and flasks. I did experiments. When I took algebra, I loved the x’s and the y’s, their purity and their power, but I knew that they stood for eggs or coins or the ages of children. Later, I had friends who were mathematicians. They were not interested in the eggs or the coins. For them, the x’s and the y’s were enough. For them, the x’s and the y’s lived in a world of their own.

Yet despite my preferences for reality, I’ve always been haunted by the conviction of Einstein, a physicist, that the deep truths of nature cannot be uncovered by