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 trajection 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:

> 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 aetheral 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 finally cosmic rays. In "L'expansion de l'espace," published in the November 1931 issue of *Revue des Questions Scientifiques,* Lemaître writes:

> 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 rep-

resented 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 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.

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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