The Nature of Scientific Reasoning

by Jacob Bronowski

1 What is the insight in which the scientist tries to see into nature? Can it indeed be called either imaginative or creative? To the literary man the question may seem merely silly. He has been taught that science is a large collection of facts; and if this is true, then the only seeing which scientists need to do is, he supposes, seeing the facts. He pictures them, the colorless professionals of science, going off to work in the morning into the universe in a neutral, unexposed state. They then expose themselves like a photographic plate. And then in the darkroom or laboratory they develop the image, so that suddenly and startlingly it appears, printed in capital letters, as a new formula for atomic energy.

2 Men who have read Balzac and Zola[1] are not deceived by the claims of these writers that they do no more than record the facts. The readers of Christopher Isherwood[2] do not take him literally when he writes "I am a camera." Yet the same readers solemnly carry with them from their school-days this foolish picture of the scientist fixing by some mechanical process the facts of nature. I have had of all people a historian tell me that science is a collection of facts, and his voice had not even the ironic rasp of one filing cabinet reproving another.

3 It seems impossible that this historian had ever studied the beginning of a scientific discovery. The Scientific Revolution can be held to begin in the year 1543 when there was brought to Copernicus, perhaps on his deathbed, the first printed copy of the book he had finished about a dozen years earlier. The thesis of this book is that the earth moves around the sun. When did Copernicus go out and record this fact with his camera? What appearance in nature prompted his outrageous guess? And in what odd sense is this guess to be called a neutral record of fact?

4 Less than 100 years after Copernicus, Kepler published (between 1609 and 1619)

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[1] Honoré de Balzac (1799-1850) and Émile Zola (1840-1902) were 19th-century French novelists.
[2] Christopher Isherwood was an English novelist and playwright (1904-1986) whose writing was the basis for the musical *Cabret*.

the three laws which describe the paths of the planets. The work of Newton and with it most of our mechanics spring from these laws.[3] They have a solid, matter-of-fact sound. For example, Kepler says that if one squares the year of a planet, one gets a number which is proportional to the cube of its average distance from the sun. Does anyone think that such a law is found by taking enough readings and then squaring and cubing everything in sight? If he does, then, as a scientist, he is doomed to a wasted life; he has as little prospect of making a scientific discovery as an electronic brain has.

5 It was not this way that Copernicus and Kepler thought, or that scientists think today. Copernicus found that the orbits of the planets would look simpler if they were looked at from the sun and not from the earth. But he did not in the first place find this by routine calculation. His first step was a leap of imagination—to lift himself from the earth, and put himself wildly, speculatively into the sun. "The earth conceives from the sun," he wrote; and "the sun rules the family of stars." We catch in his mind an image, the gesture of the virile man standing in the sun, with arms outstretched, overlooking the planets. Perhaps Copernicus took the picture from the drawings of the youth with outstretched arms which the Renaissance teachers put into their books on the proportions of the body. Perhaps he had seen Leonardo's[4] drawings of his loved pupil Salai. I do not know. To me, the gesture of Copernicus, the shining youth looking outward from the sun, is still vivid in a drawing which William Blake[5] in 1780 based on all these: the drawing which is usually called *Glad Day*.

6 Kepler's mind, we know, was filled with just such fanciful analogies; and we know what they were. Kepler wanted to relate the speeds of the planets to the musical intervals. He tried to fit the five regular solids into their orbits. None of these likenesses worked, and they have been forgotten; yet they have been and they remain the stepping stones of every creative mind. Kepler felt for his laws by way of metaphors, he searched mystically for likenesses with what he knew in every strange

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[3] Nicolaus Copernicus (1473-1543) was a Polish astronomer. Johannes Kepler (1571-1630) was a German astronomer. Isaac Newton (1642-1727) was an English physicist and mathematician.
[4] Leonardo da Vinci (1452-1519) was an Italian artist, inventor and designer.
[5] William Blake (1757-1827) was an English poet, artist and engraver.

corner of nature. And when among these guesses he hit upon his laws, he did not think of their numbers as the balancing of a cosmic bank account, but as a revelation of the unity in all nature. To us, the analogies by which Kepler listened for the movement of the planets in the music of the spheres are farfetched. Yet are they more so than the wild leap by which Rutherford and Bohr[6] in our own century found a model for the atom in, of all places, the planetary system?

7 No scientific theory is a collection of facts. It will not even do to call a theory true or false in the simple sense in which every fact is either so or not so. The Epicureans held that matter is made of atoms 2000 years ago and we are now tempted to say that their theory was true. But if we do so we confuse their notion of matter with our own. John Dalton[7] in 1808 first saw the structure of matter as we do today, and what he took from the ancients was not their theory but something richer, their image: the atom. Much of what was in Dalton’s mind was as vague as the Greek notion, and quite as mistaken. But he suddenly gave life to the new facts of chemistry and the ancient theory together, by fusing them to give what neither had: a coherent picture of how matter is linked and built up from different kinds of atoms. The act of fusion is the creative act.

8 All science is the search for unity in hidden likenesses. The search may be on a grand scale, as in the modern theories which try to link the fields of gravitation and electromagnetism. But we do not need to be browbeaten by the scale of science. There are discoveries to be made by snatching a small likeness from the air too, if it is bold enough. In 1935 the Japanese physicist Hideki Yukawa[8] wrote a paper which can still give heart to a young scientist. He took as his starting point the known fact that waves of light can sometimes behave as if they were separate pellets. From this he reasoned that the forces which hold the nucleus of an atom together might sometimes also be observed as if they were solid pellets. A schoolboy can see how thin Yukawa’s

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[6] Ernest Rutherford (1871-1937) was a British physicist who became known as the father of nuclear physics. Niels Bohr (1885-1962) was a Danish physicist who made foundational contributions to understanding atomic structure and quantum theory, for which he received the Noble Prize in Physics in 1922.

[7] John Dalton (1766-1844) was a British chemist and physicist who developed the atomic theory of matter and thus is considered a father of modern physical science.

[8] Hideki Yukawa (1907-1981) was a Japanese theoretical physicist who received the Nobel Prize in Physics in 1949.

analogy is, and his teacher would be severe with it. Yet Yukawa without a blush calculated the mass of the pellet he expected to see, and waited. He was right; his meson was found, and a range of other mesons, neither the existence nor the nature of which had been suspected before. The likeness had born fruit.

9 The scientist looks for order in the appearances of nature by exploring such likenesses. For order does not display itself of itself; if it can be said to be there at all, it is not there for the mere looking. There is no way of pointing a finger or camera at it; order must be discovered and, in a deep sense, it must be created. What we see, as we see it, is mere disorder.

10 This point has been put trenchantly in a fable by Karl Popper[9]. Suppose that someone wished to give his whole life to science. Suppose that he therefore sat down, pencil in hand, and for the next 20, 30, 40 years recorded in notebook after notebook everything that he could observe. He may be supposed to leave out nothing: today's humidity, the racing results, the level of cosmic radiation and the stock market prices and the look of Mars, all would be there. He would have compiled the most careful record of nature that has ever been made; and, dying in the calm certainty of a life well spent, he would of course leave his notebooks to the Royal Society. Would the Royal Society thank him for the treasure of a lifetime of observation? It would not. The Royal Society would treat his notebooks exactly as the English bishops have treated Joanna Southcott's box.[10] It would refuse to open them at all, because it would know without looking that the notebooks contain only a jumble of disorderly and meaningless items.

11 Science finds order and meaning in our experience, and sets about this in quite a different way. It sets about it as Newton did in the story which he himself told in his old age, and of which the schoolbooks give only a caricature. In the year 1665, when Newton was 22, the plague broke out in southern England, and the University of Cambridge was closed. Newton therefore spent the next 18 months at home, removed

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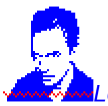
9 Karl Popper (1902-1994) was an Austrian-born British philosopher who is generally regarded as one of the greatest philosophers of science of the 20th century.

10 Southcott was a 19th-century English farm servant who claimed to be a prophet. She left behind a box that was to be opened in a time of national emergency in the presence of all the English bishops. In 1927, a bishop agreed to officiate; when the box was opened, it was found to contain only some odds and ends.

from traditional learning, at a time when he was impatient for knowledge and, in his own phrase, “I was in the prime of my age for invention.” In this eager, boyish mood, sitting one day in the garden of his windowed mother, he saw an apple fall. So far the books have the story right; we think we even know the kind of apple; tradition has it that it was a Flower of Kent. But now they miss the crux of the story. For what struck the young Newton at the sight was not the thought that the apple must be drawn to the earth by gravity; that conception was older than Newton. What struck him was the conjecture that the same force of gravity, which reaches to the top of the tree, might go on reaching out beyond the earth and its air, endlessly into space. Gravity might reach the moon: this was Newton’s new thought; and it might be gravity which holds the moon in her orbit. There and then he calculated what force from the earth (falling off as the square of the distance) would hold the moon, and compared it with the known force of gravity at tree height. The forces agreed; Newton says laconically, “I found them answer pretty nearly.” Yet they agreed only nearly: the likeness and the approximation go together, for no likeness is exact. In Newton’s science modern science is full grown.

12 It grows from a comparison. It has seized a likeness between two unlike appearances; for the apple in the summer garden and the grave moon overhead are surely as unlike in their movements as two things can be. Newton traced in them two expressions of a single concept, gravitation: and the concept (and the unity) are in that sense his free creation. The progress of science is the discovery at each step of a new order which gives unity to what had long seemed unlike.

Background and Culture Notes

*Let me tell you*

Jacob Bronowski was an English mathematician, scientist, and essayist. Born in Poland and educated in England, in 1933 he received a Ph.D. in mathematics from

Cambridge University, where he also co-edited an avant-garde literary magazine. Bronowski served as a university lecturer before entering government service during World War II; in 1945 he was an official observer of the atomic bombings of Hiroshima and Nagasaki. Throughout the 1950s he was head of research for Britain's National Coal Board, and from 1964 until his death he was a resident fellow at the Salk Institute, La Jolla, California. The author of many books, among them *Science and Human Values* (1956; 1965), *Nature and Knowledge* (1969), and *Magic, Science, and Civilization* (1978), He is best remembered in Britain for the thirteen-part BBC television series *The Ascent of Man* (1973-1974).