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THE NEW DISCOVERIES

by Philip H. Abelson

Very little human activity ever proves of much consequence in the anarchic scheme of history, and, whether fortunate or not, the fact is nonetheless irksome; men do not like to be told that they are plowing the waves.

The Roman poet Horace ventured one solution: Through art, he claimed, one could erect a monument "more permanent than bronze"—and he was right, at least in his own case. But today men are building a collective, not an individual, monument: the edifice of scientific knowledge.

The edifice has unusual properties. It is constantly being extended, tested, perfected. Ornaments are added regularly—and as regularly erased. Most unusual of all is that the edifice is being constructed by hundreds of thousands of people who, relying on standards implied in the term "scientific method," can build confidently on the foundations laid by others who may be thousands of miles—or hundreds of years—apart.

For that reason, if a scientist of 50 years ago suddenly visited a modern laboratory, he would undoubtedly be bewildered, but he could quickly be brought up to date. Unlike the wild boy of Aveyron, he would not have arrived as a blank slate in an alien culture. He would appreciate some of our pressing dilemmas—among them, that the more we learn, the less we understand. He would be at home, too, in the great areas of scholarly inquiry, though they have changed greatly since 1928.

Astronomers still observe the familiar stars but now perceive them as great nuclear reactors. They talk authoritatively of quasars, pulsars, neutron stars, and black holes, yet they hunger to know how the stars, the galaxies, and the universe were formed.

Plant biology remains of immense importance, but with our urgent needs for food and energy it has evolved from a descriptive science into an experimental one. Through biology and medicine we have eradicated some of the deadliest diseases known to man—most recently, smallpox—but the mechanisms of genetics elude us as before, and we have only just begun to understand how the mind and memory work.

The *tools* of the modern researcher might easily confound our visitor from 1928. He would be puzzled by most of the equipment in a modern research lab and astonished by the fact that the annual cost of equipment per U.S. scientist is in the tens of thousands of dollars. He would probably ask to sit down when told that throughout the world scientists speak to one another through an intricate network of teleconferencing, computer linkups, and, when necessary, the relatively mundane telephone—all made possible by continuing developments in electronics. Here we have seen a major leap forward since the 1920s.

More Nimble than the Brain

Electronics stands behind the space program and the computer. It will soon transform the banking industry, making it possible to commit errors in one's checkbook without lifting a pen. In the end, the electronics revolution will prove as important as the Industrial Revolution of the 18th and 19th centuries, though for different reasons. The Industrial Revolution was crude and based on large-scale energy use. The electronics revolution is refined: It bends energy and force to our will, much as the brain directs the use of muscles. Yet, for some tasks, electronics can be more subtle, more nimble, and more dependable than the brain.

In their simplest form, electronic measuring devices convert a physical quantity, such as light, into an electrical signal. (A familiar example is the exposure meter used in photography.) In more complex devices, the signals are further processed and decoded by medium-sized computers. In these devices thousands of miniaturized integrated circuits can now be molded into silicon chips the size of a fingernail. Each chip costs about $1.00. Sixteen years ago, an electronic device with similar capabilities would have cost $6,000. And it would have been 30,000

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THE MICROELECTRONICS REVOLUTION

Most of the technological achievements of the last two decades depend on microelectronics. Without microelectronic devices there would be no satellites, no MIRVed missiles, no reliable computers, television sets, or bank records as we know them.

In the beginning was the transistor, a small, low-powered amplifier that replaced the vacuum tube. Invented in 1948 by the team of John Bardeen, Walter H. Brattain, and William Shockley at Bell Laboratories, the transistor has now evolved into a complex arrangement of "solid-state" integrated circuits on a chip the size of a fingernail. In modern microelectronic devices the circuits are formed on these chips by photolithography, in some cases using a steered electron beam.

The theory behind integrated circuits is relatively simple. Some substances, including most metals, are excellent conductors of electricity. Others, such as rubber and glass, are poor conductors and can be used as insulators. In between are substances such as silicon that are known as semiconductors.

By introducing small impurities—a process known as "doping" —atoms of pure silicon can be given either a positive or a negative charge. If a silicon atom, which has four electrons in its outermost or "valence" shell, is doped with phosphorus, which has five electrons in its valence shell, the resulting linkup will generate one "free" electron. This extra electron is capable of carrying a negative charge and thus gives the semiconductor a negative (*n*-type) orientation.

The silicon atom can also be doped with boron, which has three electrons in its valence shell, to form a bond that is missing one electron, creating a "hole" that gives a positive (*p*-type) orientation. When an electric charge is applied to the semiconductor, the extra electrons and holes are mobilized to act as charge carriers.

As in the first transistor, the *p*-type and *n*-type semiconductors can be arranged in layers to conduct electric charges in only one direction within a circuit; thus the circuit may be either "on" or "off." A certain electrical "input" will give a predetermined "output"—an arrangement called a "gate" that is the basic unit of electronic logic.

A unit that can go on and off in a predictable fashion can also be made to represent "yes" or "no"—or 1 and 0, the constituents of the binary number system used in all computers.

times as big. What Thomas Carlyle said of men may especially be applied to the scientist: "Without tools he is nothing; with tools he is all."

The most glamorous new tool is the laser. A laser can be made to produce a steady stream of light, but is usually adjusted to emit an intense, controllable, monochromatic pulse that may be as short as one-trillionth of a second (one *picosecond*). These features permit sharp focusing of the light as well as precise timing.

Most Americans are now familiar with the use of a laser to repair detached retinas, cut steel sheets, or conduct high-accuracy land surveying. Some lasers are being used in endeavors to achieve nuclear fusion. But the most important applications will surely come in chemistry. Chemists have long known that some chemical reactions occur rapidly; in many instances, intermediate products are formed during a chemical process that may last for no more than one picosecond. (In some plants, the absorption of a photon of light takes *less* than one picosecond.) Lasers now are being used, in what is called *picosecond chemistry*, to make these reactions finally accessible to study.

Pulsars and Quasars

The laser is only one of many instruments that have increased the precision and speed of observation. At one time, for example, the chemical analysis of a typical rock required a one-gram sample and a week's time. The process resembled a python digesting a ram. The rock was first ground to a fine powder, then subjected to long periods of "digestion" by a mixture of corrosive acids until it was dissolved. A skilled chemist might complete a dozen analyses in a week. Today, using an electron microprobe, a sharply focused electron beam hits a tiny spot on the surface of the specimen and produces X-rays whose character will vary with that of the rock's constituent elements. These X-rays are then resolved and interpreted electronically. The process requires 10 minutes and one-billionth of a gram of rock.

In astronomy, intriguing new discoveries have come from the use of radiotelescopes—those dish-shaped receivers up to 300 feet in diameter that are exquisitely sensitive to radio signals reaching Earth from outer space. Until World War II, most astronomers had to rely on photographic plates to record their observations—a good technique as far as it went, rather like a silent movie about the Vienna Boys Choir. Now the great observatories have been converted into electronic laboratories, and their records are stored on magnetic tapes. Radiotelescopes helped astronomers determine the shape of our galaxy, the Milky Way—basically a flat spiral with a bulge near the center. Signals received by radiotelescopes also revealed that there were powerful radio stations in the sky, some of them switching

"BEAUTY," "TRUTH," AND "STRANGENESS"

In 1964 physicists Murray Gell-Mann and George Zweig independently predicted the existence of a fundamental, subnuclear particle that cannot be broken down into smaller constituents. They called the particle a *quark* (the word comes from James Joyce's *Finnegans Wake*), and theorized that quarks are building blocks that combine to form the atomic units known as *hadrons*, a family that includes protons, neutrons, lambdas, and mesons. (An unrelated family of atomic units, the *leptons*, includes electrons, neutrinos, and muons.)

Four types of quarks are currently believed to exist, distinguishable by the peculiar quantum characteristics of "up," "down," "strangeness," or "charm." All quarks have a fractional electric charge, angular momentum, and mass. For each type of quark there is also an *antiquark*, with opposite characteristics.

Quarks are characterized by their sensitivity to the so-called *strong* force that binds quarks together to form hadrons (the Greek word *hadron* means "stout" or "strong"). One up and two down quarks are combined by the strong force to form a neutron. One down and two up quarks form a proton. One up, one down, and one strange quark form a lambda. A quark-antiquark combination produces a particle of the meson group.

Although quarks have yet to be isolated in the laboratory (the strong force may bind them so tightly that isolation is impossible), recent evidence suggests that two more kinds of quarks exist. Their proposed names: "truth" and "beauty." Until such quarks are actually isolated, however, modern physics may take comfort in St. Paul's Epistle to the Hebrews: "Through faith we understand that the worlds were framed by the word of God, so that things which are seen were not made of things which do appear."

off and on as often as 30 times per second. Called *pulsars*, these signals are probably emitted by rotating neutron stars.

By using radiotelescopes in combination, moreover, it is possible to determine the precise location of a radio source in space through a procedure similar to "triangulation" used in navigation on Earth. Such cooperative activity enabled astronomers to detect and describe the first *quasars*—essentially radio signals from "quasi-stellar" objects with large *red shifts*. Red shift refers to the displacement of light toward the red end of the spectrum; it is approximately proportional to the velocity of a star or other stellar object as it recedes from Earth.

Another advance in astronomy has been the development of a more sensitive means of measuring light. Until recently the

ONE MAN'S REVOLUTION

Notions of how old scientific theories give way to new tend to be shaped not by scientists but by historians and philosophers of science. What is still probably the most generally held opinion among both scientists and the public is one that was shaped during the 1930s and 1940s by the school of positivist philosophers known as the Vienna Circle.

According to this view, science is a strictly logical process. Scientists propose theories on the basis of inductive logic, and confirm or refute them by experimental tests. When old theories fail, new theories are proposed and adopted because of their greater explanatory power, and science thus moves ever closer to the truth.

Logical empiricism, as this view is called, still has its defenders, but many philosophers and historians of science now favor perceptions of the scientific enterprise that take human factors into account as well as the purely logical structure.

Perhaps the principal force behind this change was a book published 16 years ago that cut blithely across the demarcation lines between the philosophy, history, and sociology of science. *The Structure of Scientific Revolutions* is a landmark in intellectual history that has attracted attention far beyond its own immediate field.

Thomas S. Kuhn, its author, was trained as a solid-state physicist but works as a historian at Princeton and the Institute for Advanced Study. His book still evokes a set of reactions that defies any general consensus. Common among science historians is the view that it is both brilliant and refutable.

"My own attitude toward the book," says one scholar, "is the same as toward a number of other books, that they are classics in the sense that they have been completely disproved in detail by the professionals in the field and yet they somehow survive."

Kuhn's thesis, in rough outline, goes as follows. Science is not the steady, cumulative acquisition of knowledge that is portrayed in the textbooks. Rather, it is a series of peaceful interludes punctuated by intellectually violent revolutions. During the interludes, scientists are guided by a set of theories, standards, and methods that Kuhn refers to as a "paradigm."

ability of telescopes to make out dim and distant objects was limited by a faint, ever-present glow throughout the sky. (Even when the telescope is pointed to areas where there are no stars, a photographic plate receives some light.) Using electronic detectors, astronomers can reduce this airglow effect almost as easily as adjusting a car's rearview mirror for night driving. They can

The paradigm is the basis of the research tradition; it defines which problems are interesting and which are irrelevant. During the paradigm-governed interludes, called periods of "normal science" by Kuhn, scientists essentially solve puzzles generated by the paradigm. Study of mechanics after Newton's *Principia* is one example of a period of normal science; astronomy after Copernicus is another.

But the tranquility of normal science does not last. Sooner or later, scientists trying to extend the paradigm find that there are puzzles they cannot solve. The time comes when these puzzles can be ignored no longer. Then the field enters into crisis, such as befell the phlogiston theory before the understanding of oxygen.

At this point, a new paradigm may be proposed, its underlying discoveries almost always being made, Kuhn states, by men who are "either very young or very new to the field whose paradigm they change." But defenders of the old paradigm patch it up with ad hoc fixes, and the battle is joined.

The means by which this battle is waged is central to the thesis because in Kuhn's view, nonrational factors play an essential role. Logic and experiment, says Kuhn, are not sufficient: "The competition between paradigms is not the sort of battle that can be resolved by proofs." In fact the transfer of allegiance from one paradigm to another "is a conversion experience that cannot be forced."

Nor can a new paradigm build on the one it succeeds; it can only supplant it. Science is not the cumulative process portrayed in the textbooks; it is a succession of revolutions, in each of which one conceptual world view is replaced by another. But Kuhn sees no ground for believing that the new paradigm gives a better understanding of the world than did the old. We may, says Kuhn, "have to relinquish the notion, explicit or implicit, that changes of paradigm carry scientists and those who learn from them closer and closer to the truth."

Since Kuhn does not permit truth to be a criterion of scientific theories, he would presumably not claim his own theory to be true. But if causing a revolution is the hallmark of a superior paradigm, *The Structure of Scientific Revolutions* has been a resounding success.

—Nicholas Wade © *1977* Science

now view objects so distant that the light that reaches us began its journey 10 billion years ago. The vistas opened by such research are truly cosmic: the detection of events at the far reaches of the universe, of events at the beginning of time, the creation and evolution of galaxies, the birth and death of stars.

In another direction, scientists have begun to peer deeper into "inner space"—the human body. Genetics continues to puzzle researchers, but there has been some progress. The function of chromosomal DNA as the informational material for heredity has been established. We know the gross structure of DNA, including the pairing of DNA strands portrayed in the famous Watson-Crick double helix. But scientists still don't know what turns a gene "on" and "off." That is, what processes direct genes toward that complex series of steps that culminates in a new organism?

One way to find out is to isolate specific genes and work with them in test tubes. The best way to prepare these genes involves what is popularly known as "gene-splicing," a method based on the 1972 discovery of *restriction enzymes*. These enzymes, of which about 30 are known, split DNA in highly specific ways. Afterwards, one strand of the DNA protrudes beyond the other. The two pieces of the chromosome can be rejoined by what amounts to splicing.

Insoluble Puzzles?

Alternatively, two *different* chromosomes can be split, and then part of one can be spliced onto part of the other to create an entirely new form of DNA. This "recombinant" DNA can be introduced into bacteria; there, biological machinery will produce more of the DNA along with what, for the bacteria, are novel protein products.*

The deepest mysteries in the biomedical sciences surround the workings of the brain. People knew thousands of years ago that extracts from the opium poppy could relieve pain, ease anxiety, produce euphoria, or help bring sleep. During the past five years, scientists have discovered that the human nervous system makes its own opiates, different chemically from those of the poppy but producing similar effects. These substances were found to be *pentapeptides* (compounds formed by the union of five amino acids), and it was a simple matter to improve on nature by synthesizing a variant 50 times more powerful than morphine. Whatever their ultimate therapeutic value, the brain's own opiates may provide a tool for studying the nerve pathways responsible for pain, emotion—even for the thrill of discovery.

The scientific method is most effective, of course, when a

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*Concerned about the consequences of such work, the National Institutes of Health in 1976 published guidelines governing recombinant DNA research. The rules provide for separation of altered organisms and require that research take place only on organisms incapable of life outside the laboratory.

problem can be separated into simple, solvable parts. Some biological phenomena are extremely complex; others are virtually inaccessible to observation. One goal that is likely to be approached only slowly for these reasons is control of cancer, which is not one disease but hundreds. Another is genetic engineering; complex ties among the biological systems that control growth guarantee that even minor tinkering remains distant, though not unrealistic. Far less probable is the much-publicized "cloning" of human beings or the extension of our life span much beyond the Biblical three-score-and-ten. Events will surely demonstrate that the answers to some questions are beyond human ingenuity.

Our visitor from 1928 would certainly recognize that problem. He would recognize other things as well, notably that the basic nature of scientific inquiry remains essentially what it was a half-century ago. It is hard work. When new ideas and insights occur, they come from individuals. In general they come from a person who has been immersed in a problem (like Archimedes in his bath when he shouted "Eureka!") and who has wrestled with a set of frustrating puzzles and contradictions until a light dawned.

The individual scientist's quest is still largely driven by the human desire to be the first to explore, the first to reach a new plateau of knowledge. Scientists will endure long periods of struggle and disappointment to enjoy the sudden pleasure of a new insight—followed by the reward of professional acclaim and, more rarely, a Nobel Prize. Do these motives seem impure? Perhaps they are. But the motives will be forgotten; the legacy to science will not.