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# The Indispensable Tools of Science

Instruments are unifying elements which help self-centered disciplines shed their isolationism.

Paul E. Klopsteg

By century-old custom, a retiring president of the American Association for the Advancement of Science produces a dissertation, to be delivered as his retiring address, on a subject which has occupied an important place in his career.

The 50th anniversary of my membership in the Association is just over the horizon. During these interesting years it has been my good fortune to have been intellectually and physically concerned with the instruments of science—the indispensable tools of science. Gladly do I avail myself of the traditional prerogative to draw together some facts and ideas regarding the role of instruments, whether in the exploration of the unknown or the elucidation of the known.

Throughout the half century of my interest in science I have been impressed with the importance of striving for perfection in transmitting ideas by means of words. Expressing an idea with clarity resembles building accuracy into an instrument. With this in mind, I shall try to tell you what the term *instrument* means to me; but let me first relate an experience apposite to the subject.

An attempt to define the word is identified in my memory with the year 1940. The work of the National Defense Research Committee was getting under way. The committee established numerous divisions, one of which, division D, was under the supervision of the distinguished scientist who was president of this association 25 years ago, the late Karl T. Compton. A section of the division was designated "D-3: Instruments." Its members were long experienced in the means and methods of experiment. During the organizing period we held weekly meetings in Washington to make plans and generate ideas. As we were trying at one meeting, with Compton present, to stake out boundaries for the activities of the section, we put the question to him: "Karl, what is an instrument?" After moments of seeming concentration his reply was: "An instrument is something which doesn't belong in any other section."

The sober implication of this whimsical remark is impressive when one wrestles with the problem of defining the term. One concludes that neither a single nor a simple definition can be easily contrived to meet adequately all the situations in which the word might be used.

Broadly, in science, instruments are the physical means for observation and experimentation directed to securing and utilizing information. Specifically, an instrument may be one of several things:

1) A device in which known physical principles are applied to increase one's perceptivity of natural phenomena, or to render observable otherwise completely elusive phenomena. It is an amplifier for sensory perception.

2) Means for measuring whatever attributes of a physical entity are susceptible of quantitative treatment. It provides numbers which uniquely describe the characteristics observed.

3) Means by which response to a condition may be recorded, or applied to the condition which elicits the response. It makes possible the automatic control of a condition, as in a servomechanism.

4) Means by which recorded information may be treated and processed to make it accessible to evaluation, thereby vastly decreasing the drudgery of manipulating data, or, indeed, making their evaluation feasible.

We shall take for granted what every scientist knows—namely, that observation, measurement, and control, whether in the laboratory or the field, require something more than instruments. The utility of the instrument depends on the availability of auxiliary devices and supplies, the naming of which would be like reading off the index of a catalog of laboratory apparatus and supplies.

To say that instruments with their associated apparatus occupy a place of utmost significance to research, both in advancing basic knowledge and in applying it for human betterment, is to say the obvious. Most research depends profoundly on instruments. Not until an advanced idea, developed by logic into a theory, has been subjected to searching experiment can it attain stability of status. And not until the experiment has been independently repeated and its results confirmed can the theory become assimilated in the body of knowledge. Thus do ideas, forged by logic into theories, and theories, tried and tested with instruments, become science.

It is noteworthy that among the 138 Nobel laureates in physics and chemistry from 1901 through 1960, this high recognition was accorded 112 of them for research in which instruments were dominant. In the 26 instances of theoretical work, the theories became firmly established by experiment and through successful application in further

Dr. Klopsteg, retiring president of the AAAS, is special consultant to the director, National Science Foundation, Washington, D.C. This article is the text of his AAAS presidential address, delivered 28 December before the 127th meeting of the American Association for the Advancement of Science, in New York.

research. But, conversely, theory was also of key significance in the work of the 112 who were distinguished for superb experimental insight. Clearly, there can be no dichotomy between theory and experiment. Without their interaction, there is no research.

### The Genesis of Primitive Science

Come, now, if you will, on a speculative excursion into prehistory. Assume the era in which the species *sapiens* emerged from the genus *Homo* to have been contemporaneous with the dawning of reason in man's mind. We may then suppose that this period also marked his becoming first aware, and then observant, of those phenomena which most directly impinged on his existence. This would mark the beginning of retention of some knowledge of nature, and would therefore mark the genesis of primitive science.

The first step must have been taken as he perceived the things and events in his surroundings. These were either commonplace and routine or, on rare occasions, cataclysmic. There were sunshine and clouds, wind and fog. Occasionally he beheld lightning, thunder, tornadoes and hurricanes. Sometimes the sun became darkened in a clear sky, and more often the same thing happened to the moon. When light failed, he could not see. There was heat, and absence of it, and he had little trouble recognizing hot and cold. He heard the rushing of water in streams and on the beach, and he saw the trees sway, accompanied by other sounds of rushing. He saw renewal of life in the bursting bud and sprouting seed. New life in animals and man seemingly began sometime prior to birth. He perceived development and growth, from infancy to maturity, then decline to old age and death, in repetitive cycles. Such things and events were the fabric of the mysteries of his environment and a challenge to his understanding.

Among earliest man, individuals who were observant and curious about the how and why of things developed an image of their circumscribed world which was a composite of these physical and biological bits. The primitive prototype of the modern scholar noted relations among phenomena and saw both similarities and differences in the appearances and structures of plants and animals. When he tried to clarify his picture, with reason not quite measuring up to the task, his desire for understanding had at first to be satisfied with superstitions and with assumptions about mysterious forces having no counterpart in his experience. Parenthetically, and unfortunately, it must be said that this situation still exists among many people in many places, not all of them in underdeveloped countries. Through improved observation and improving reason came the beginning of order, the recognition of some identifiable relations among phenomena. Recognizing and pondering, and reconciling and harmonizing ideas, became matters of consequence to his intellectual development. Man became a philosopher of nature. This he remained through the millenniums during which his ability to observe and think and reason and understand were evolving. But so long as man's intellect was centered on exercises in logic, so long did the infancy of science persist.

### Concepts of Time and Distance

It may be surmised that the second feeble step in the gradual emergence of science from earliest infancy was taken when man grasped the concepts of time and distance and tried to express them in terms suited to his needs. Such terms, in his world image, lay near at hand, and, with whatever simple system of counting he had, lent themselves to numerical description. Time was probably first identified with the cycle of waking and sleeping and, for longer intervals, with the lunar cycle. Distances were first expressed in dimensions derived from the body, such as arm span, hand span, length of forearm and foot, and pace. Greater lengths could be described by the stone's throw and the arrow shot and, among nomads, by the day's journey.

If, in truth, early man did find such ways of expressing time and distance, his success probably came not so much from an intellectual quest for definitive knowledge as from efforts to satisfy his need for better communication. Within the implications of this thought is the inference that progress in science depends not solely on measurement. In part, man's earliest efforts to comprehend, in his groping for order and system, probably led to his efforts to confirm his experience with simple experiments. When he had learned to reinforce reason with skill, towards better understanding of his environment, however unsophisticated those first efforts must now seem, he was creating a small base from which to extend his explorations. Measurement, with instruments of special devising, came later.

### Emergence from the Past

Suppose we leave him there, and hasten across the millenniums for which present information depends for the most part on conjecture and interpretation to the era of the first inscribed records, from which some facts may be gleaned. Out of later graphic records it is possible to construct pictures of the towering personalities who are associated with the emergence of science from the dim past. Let us fix our attention on a few of the most notable among them (*1*).

Democritus, great thinker and natural philosopher of the 5th century B.C., in proposing the concept of the atom as the smallest, indivisible, invisible, and indestructible particle, laid the foundations of 17th-century atomic theory. The beginning of modern science is often associated with Thales of Miletus, who lived during the century before Democritus. Thales and his successors comprise that remarkable group of men known as the pre-Socratics. Thales, with his idea of the unity of nature; Pythagoras, author of mathematical physics; Leucippus and Democritus, the first to conceive of the atomistic theory of matter—all of them had profound thoughts about nature. With them was born the idea that theory must fit observation—"save the phenomena," as the Greeks had it. Yet no one of them ever thought of an *experiment* designed to relate theory to fact.

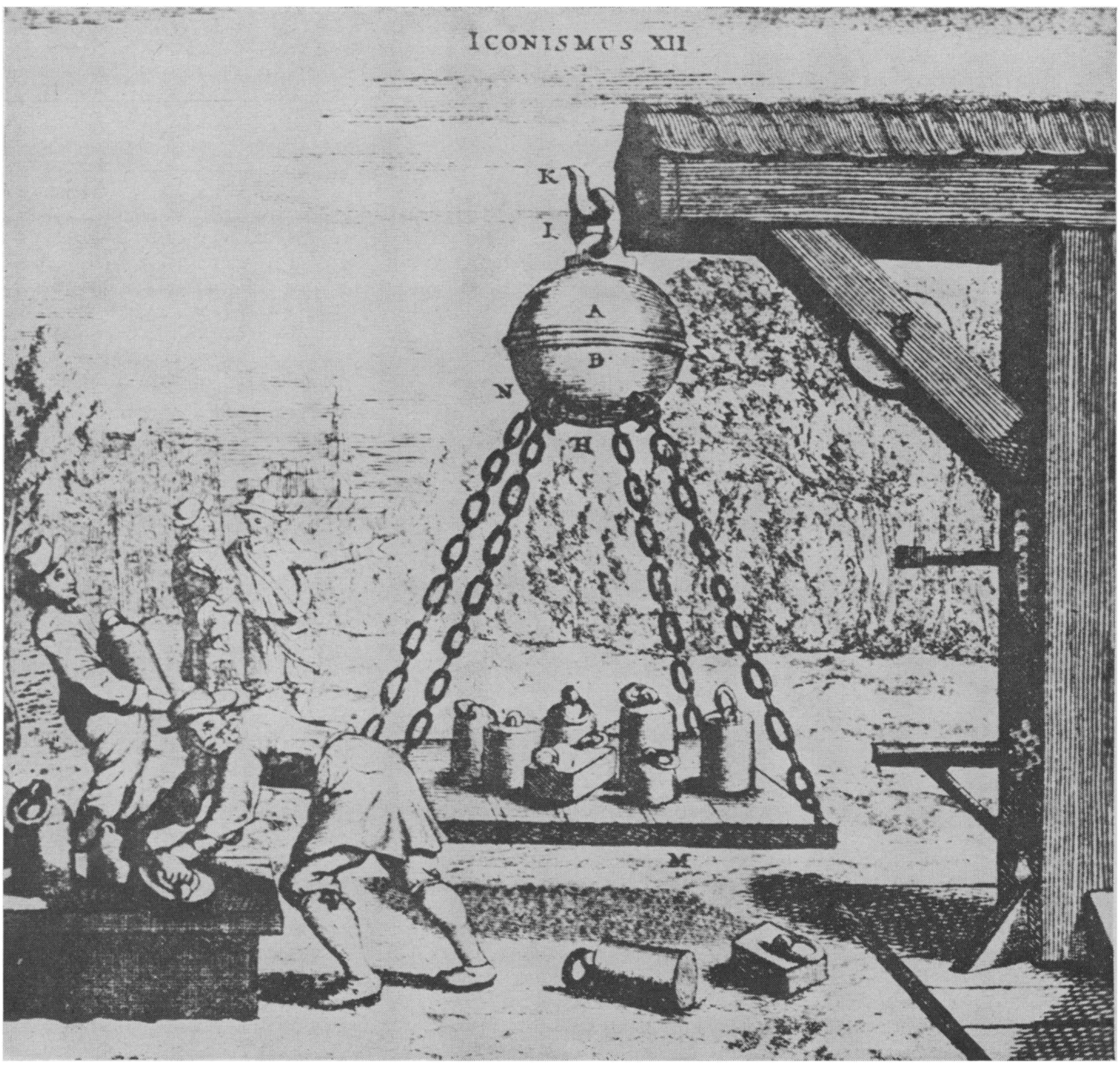
### Aristotle

Aristotle came upon the scene about a century after Democritus. His philosophy profoundly influenced the evolution of thought during the next 2000 years. His "reality of ideas," probably derived from Plato's views about reality, his codification of the rules of logic, his scientific habit of mind, and the veneration accorded him as "the master of those who know" by the succeeding generations of scholars resulted, as Dryden has said, in "making his torch their universal light." When Aristotle's writings appeared in the West, in the 12th century, they were overwhelmingly effective, and for the next three centuries they dominated scientific thought in all but a few areas. Although the Aristotelian view emphasized observation as the crucible for testing theory, its potential in advancing science was impaired by the Greek ignorance of experiment. Hence the working scientist was deprived of the powerful aid of experimental fact. "Experimental fact" is generally established by observation or measurement with instruments.

## Galileo

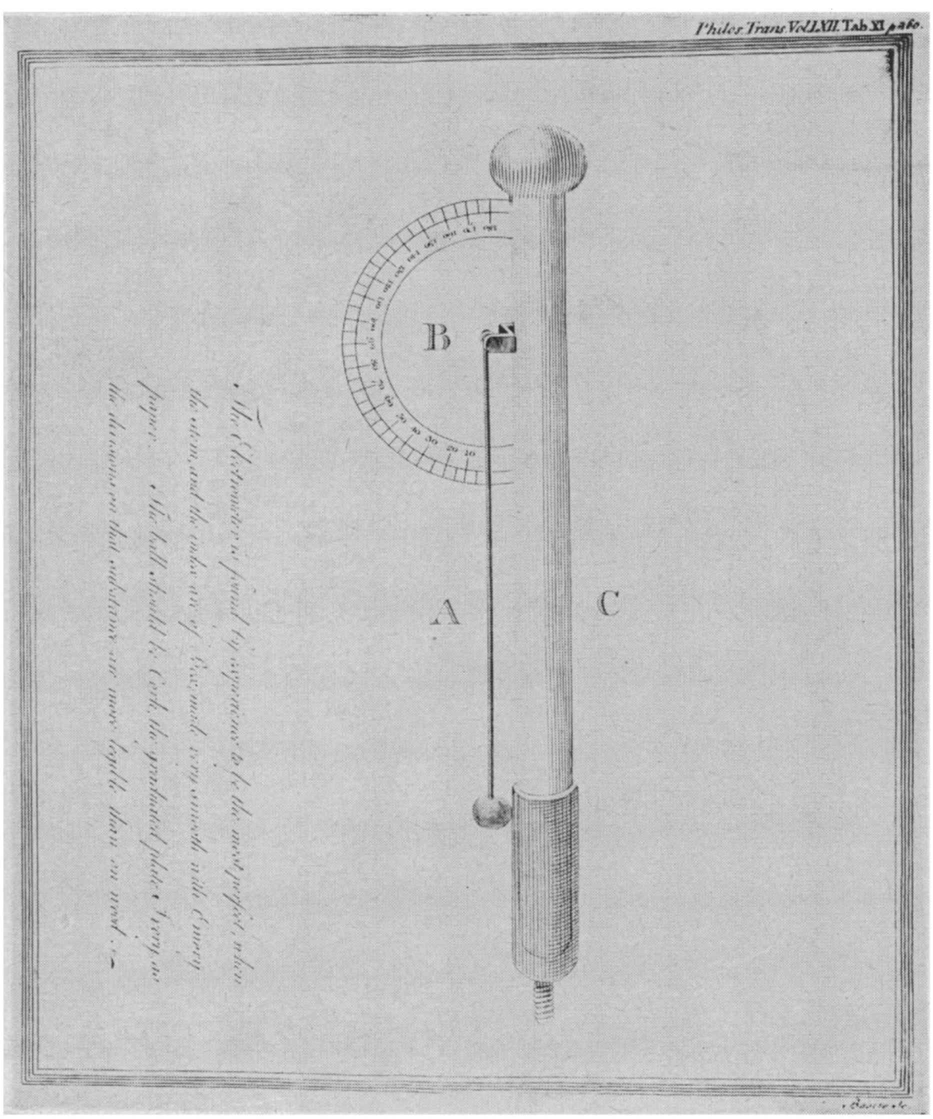
Galileo Galilei stands as our symbol of the new spirit—the "new experimental philosophy," as it was called—which awakened Europe in the 16th and 17th centuries. Galileo adopted the best elements in Greek science—first, logic, and particularly mathematical logic, and second, the insistence that theory must lead to agreement with observation. To this he added the missing ingredient—experimentation: not mere observation of the passing events of nature but deliberate intrusion to shape events to the observer's purposes. He was an accomplished craftsman who personally designed and constructed numerous telescopes, and there is no doubt about his skill in using them. He was the first to scan the heavens with the telescope, to become the discoverer of four of Jupiter's satellites and the phases of Venus. He invented other instruments, among them the forerunner of the thermometer. Shortly before his death Galileo designed a pendulum clock.

However appealing some of the stories of Galileo's exploits may be,



Guericke's experiments with Magdeburg hemispheres. [Library of Congress] such as the Leaning Tower story and the swinging-chandelier story, we know them now to be fiction created by his admirers. Others rolled balls down inclined planes and dropped rocks from towers before Galileo. But none of this detracts from the essential character of his resolute adherence to the idea that, in science, experiment is the proof of the pudding. Galileo and his like-thinking contemporaries initiated a "new experimental philosophy"—indeed, a philosophy which recognized the need for new tools, the tools of the experimenter, *instruments*. These soon gave exciting evidence that here were the means, and here was the way, for soundly and solidly building the structure of science. The growing interaction between theory and experiment, like feedback in a regenerative circuit, set off an explosion of ideas and produced a spectacular, unprecedented rise in the level of man's comprehension of nature.

This appraisal of the effect of Galileo's "new experimental philosophy" leads logically to an examination of how the availability of a new instrument may have both immediate and far-reaching effects on the state of knowledge. It would be an absorbing occupation to write a treatise on the consequences of the invention of specific instruments, where many case histories might be fully developed. The Harvard Case Histories in Experimental Science are indicative of possibilities. Within the limits of this article I cannot do more than select and appraise a few examples, having in view their role and the indelible imprints which they left.



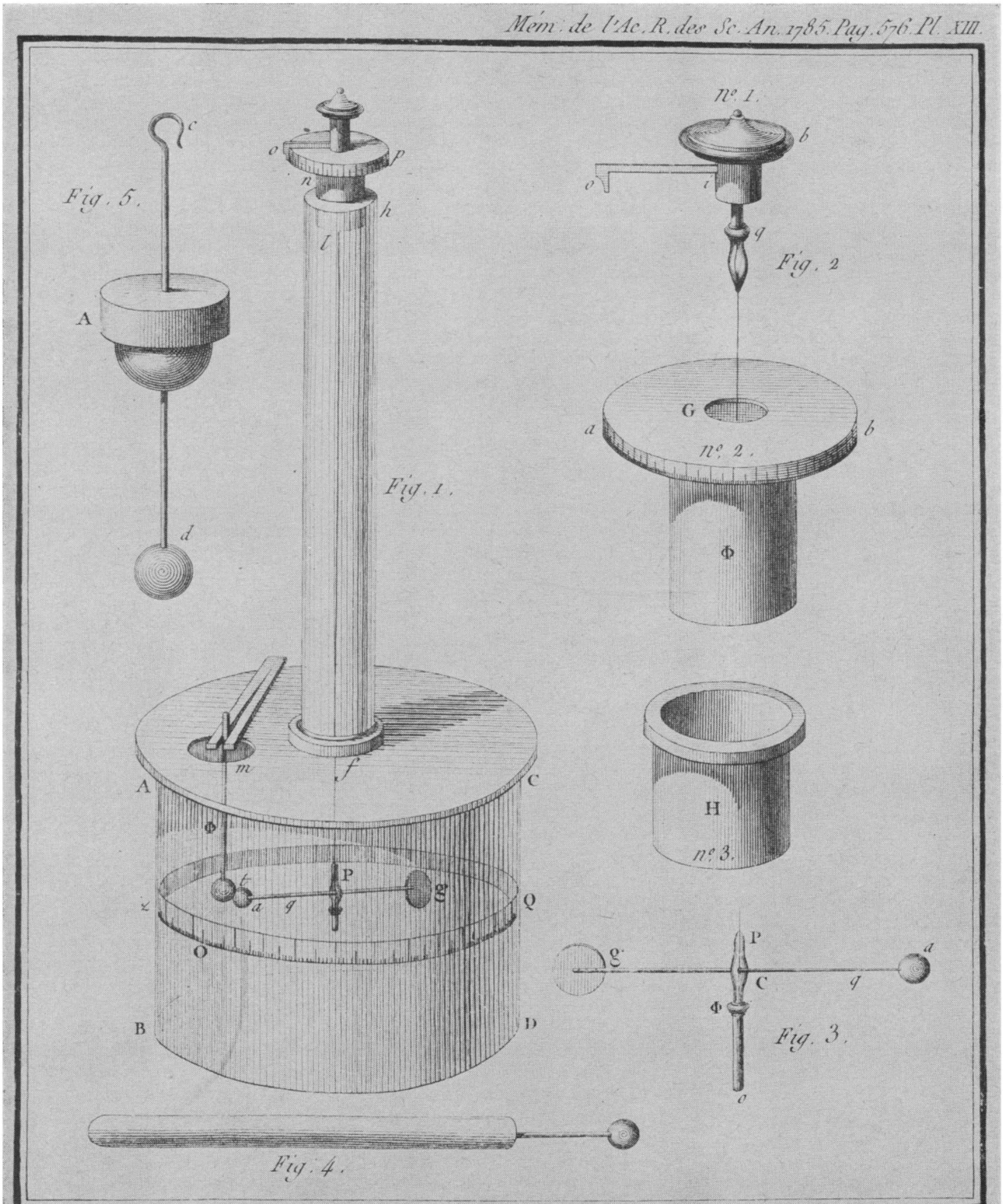

Henly's electrometer. [Burndy Library, Norwalk, Conn.]

## Barometer and Air Pump

Prior to the 17th century, nature was "known" to abhor a vacuum. Driven by his desire to see how high a column of mercury would be supported by a vacuum, and thus to learn the extent of nature's abhorrence, Torricelli in 1643 invented the mercury barometer. In modified form, it was also a manometer. He correctly reasoned that the height of the barometer measures the pressure of the earth's "sea of air." Its indications of that pressure and of its variations have made the barometer one of the outstanding inventions among instruments. To test the assertion we need only reflect on how atmospheric pressure affects many physical and biological processes and events, and consider that, without means for measuring pressure, significant studies in the atmospheric sciences could not be made. Nor would it be possible to forecast weather, or to navigate aircraft with any degree of reliability.

Since its invention the barometer has been of inestimable value both in research and in its service to man. From its original form to the mercurial barometer of today—still the primary standard for atmospheric pressure—it has undergone great refinement. Secondary forms, employing an aneroid capsule, are widely used as portable barometers and altimeters, calibrated to the mercury standard. Combined with electronic circuitry, the aneroid made the radiosonde possible. This essential meteorological instrument is comparable in importance to the original invention of Torricelli.

Torricelli of course knew that the space above the mercury in his barometer contained no air. It was a vacuum created by man, subsequently called the "Torricellian" vacuum. A few years later, in 1651, von Guericke developed the first pump to remove air from large enclosed spaces. An improved pump, built by Hooke and used by Boyle, about eight years after von Guericke's, and later models, further improved, deeply stirred the experimenters' imaginations. Astonishing demonstrations were made of the effects of atmospheric pressure and the role of the atmosphere. It was shown to be essential to combustion and respiration. In the absence of air, sound was not transmitted. Objects were found to fall at the same rate in a vacuum, but electric and magnetic forces were not affected.




Coulomb's torsion balance. [Smithsonian Institution]

In its later versions the air pump made possible the gas-discharge tube, the forerunner of the x-ray tube and the principal means of revealing the nature of electrical phenomena in gases. It was the heart of the researches of J. J. Thompson, Rutherford, and many others in studies of electrons and ions and of radioactivity. Its innumerable descendants among the mechanical, diffusion, and ionic types of pumps are the foundation for segments of modern technology too vast for simple comprehension. Of equal importance is their function in the accelerators of high-energy physics, and in the search for methods to bring about and control nuclear fusion. Only a few decades ago a vacuum of $10^{-6}$ millimeter of mercury was considered excellent, one of $10^{-8}$ exceptional, and a report of anything beyond that, either error or prevarication. Today's reports nonchalantly talk about a vacuum of $10^{-10}$ and beyond, which approaches the conditions of outer space, and no one would doubt them. It is an understatement to say that without the air pump, space science would be under a serious handicap.

### Pneumatic Trough

Related to the barometer and air pump, because of its dependence on atmospheric pressure, is the pneumatic trough, invented by Stephen Hales in 1727. It consisted of a narrow-necked glass container, filled with water and inverted, with its mouth immersed in another container or trough, and a gas-conducting tube leading into it. With this simple device, measurements could be made of gas volumes released in chemical reactions. It was essential to the work of Priestley, Gay-Lussac, and Avogadro, out of which came understanding of the physics and chemistry of gases. Priestley, for example, in 1772 substituted mercury for water and discovered the water solubility of gases, and he was using mercury in the trough when he discovered oxygen.

### Electroscope

Though some electrical phenomena were discovered many centuries ago, electricity could not be systematically and quantitatively studied before the electroscope appeared. W. Cameron Walker has pointed out how dependent progress in electricity was on the invention and improvement of instruments. His observation is validated by the history of electrostatics, culminating in the discovery of current electricity. Volta invented the voltaic pile with the aid of means for detecting the extremely minute charges produced by the contact of dissimilar metals. Up to the time of Volta, the familiar gold-leaf electroscope was the most sensitive detector of electric charges. Simple as it is, it emerged from nearly a century of improvement, beginning with Hauksbee's use of thin leaf brass as a charge detector. Henly in 1770 made an instrument giving numerical indications, called by him a quadrant electrometer, for ascertaining relative amounts of electricity in a Leyden jar, and for finding the conducting ability of different metals. Volta developed a straw electrometer, which he employed with a condenser in his multiplying electroscope. Bennet's instrument, the last of many before 1779, was the most sensitive and was used by Volta between 1790 and 1800.

The gold-leaf electroscope and its derivatives are still widely, if not universally, used in demonstrations and laboratory experiments in electrostatics. Notably, the electroscope, both with leaf metal and the metallized quartz fiber, became the essential instrument in the work of the Curies and of Rutherford, Geiger, Hahn, Meitner, and others in their pioneer explorations in radioactivity. It is impressive indeed to realize the extent to which the present state of knowledge of nuclear physics is indebted to measurements made possible by the electroscope.

### Torsion Balance

The torsion balance, devised by Coulomb and presented by him to the French Academy in 1784, made possible the measurement of the very small forces between minute charges of electricity and between weak magnetic poles. The sensitivity of this instrument, heightened when used as a torsion pendulum, enabled Coulomb to verify the inverse-square law for both electrostatic and magnetic forces of attraction and repulsion. Although Coulomb was not the the first to suggest the inverse-square hypothesis in electricity, he *was* the first to present convincing experimental support for it, thus establishing it as the quantitative law that quite properly bears his name. For the first time this made possible the assignment of numbers to the electrical or magnetic states of objects and the application of mathematical procedures in the study of electricity and magnetism. To quote Roller: "Eighteenth century mathematics had to a very large degree developed along lines applicable to Newtonian mechanics, and with the formulation of electrical science in quantitative terms so analogous to mechanics, electricity became thoroughly amenable to mathematical treatment . . ." The effects on the increase in the understanding of electrical and magnetic phenomena in the 19th century were striking if not spectacular. In the modern Washington vernacular, it was a "breakthrough."

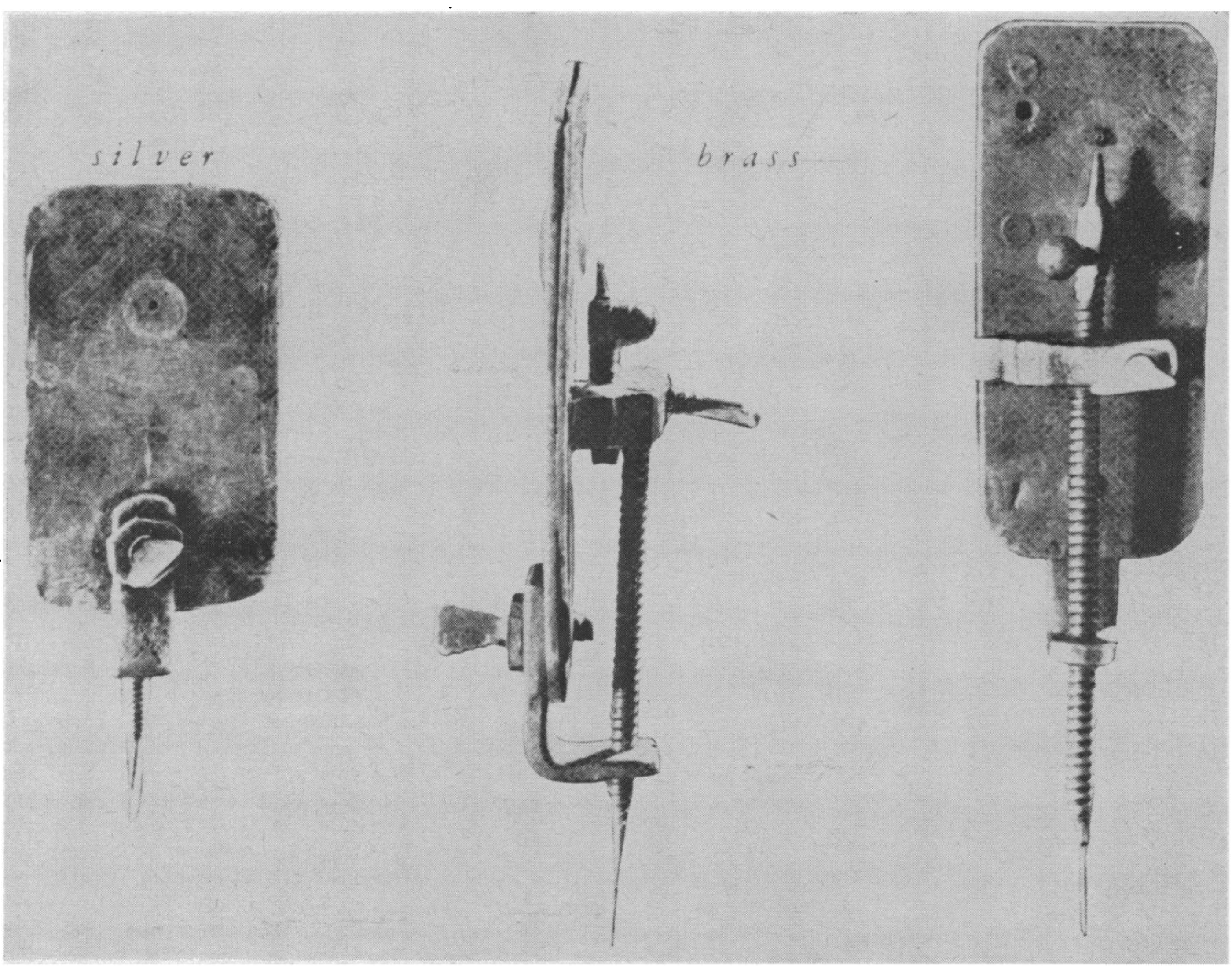
The torsion balance, used as a torsion pendulum by Henry Cavendish, scored another great advance in another application, where far smaller forces had to be measured—namely, the gravitational attraction between known masses in the laboratory. The Cavendish experiment, reported in 1798, proved to be a feat of rare skill and ingenuity, with a relatively simple instrument. In 1687 Newton published his law of universal gravitation, basing it on Kepler's laws of a century earlier. It remained for Cavendish, with an instrument designed independently of Coulomb by the Reverend John Michell of the Royal Society, but never used by him, to measure the force between spheres of lead 2 and 8 inches in diameter, respectively. From this measurement and the known weight of one of the experimental spheres, the gravitational constant and the mass of the earth were obtained, and from its volume and mass, its average density became known. The values found were within 1 or 2 percent of those determined by others a century later.

The Cavendish experiment was significant for several reasons. It accurately measured forces so small that they had escaped observation prior to that time. It provided reliable information from which the masses of bodies in the solar system could be computed. Moreover, the torsion balance of Cavendish, modified in detail and greatly refined, became an important tool in geophysical exploration earlier in this century. With it, gravity gradients could be ascertained and mapped, to provide information about hidden geological structures of special interest in petroleum prospecting.

## Microscope

Research with the highly developed microscope of today stands in direct line of descent from notable research done with a simple, strongly converging lens made of a bead of glass. It was an instrument of such almost incredible simplicity that Leeuwenhoek used when in 1675 he discovered protozoa and clearly observed red blood corpuscles, and when in 1681 he discovered bacteria, unicellular organisms much smaller than the protozoa. The compound microscope seems first to have been devised by Janssen, about 1590. It is possible, also, that Galileo converted the optics of a telescope to those of a microscope, about 1610. It seems established that Galileo's fellow-members of the Accademia dei Lincei made the first observations with a compound microscope between 1611 and 1624, but nothing of significance was recorded during this period. The publication of Robert Hooke's *Micrographia* in 1665, however, drew wide attention and produced a great burst of researches in microscopy. Among them were the work of Malpighi, Leeuwenhoek, and Swammerdam. These 17th-century microscopists became qualified to reject the authority of the classical authors, who lacked the microscope, since this new tool opened to them a biological world totally unknown to the ancients. It revealed structures which suggested mechanism, thus supporting a mechanistic view of physiological processes. It directed interest to the lower animals and helped zoology to become an independent science. By the discovery of microorganisms, it vastly expanded the domain of biology. It helped to overthrow the theory of spontaneous generation and established the concept that the cell is the basic unit of any living organism.

All of biology is deeply rooted in ideas which could come only out of the revelations of the microscope. These were limited by the optical imperfections of the early instruments—limitations which were largely removed with the development of lens systems which flattened the image field and corrected for refractive color. These removed spurious patterns from the image and increased the observer's confidence in the reality of what he saw. The latter part of the 19th century brought increasing excellence in the techniques of preparation of materials for microscopic study. Oil-immersion of objectives and condensers increased magnifications. Dark-field illumination and, more recently, phase-contrast techniques, brought within view details not revealed by ordinary transmitted light.




Three microscopes made and used by Antoni van Leeuwenhoek between 1673 and 1723. [National Museum for the History of Science, Leiden; Smithsonian Institution]

Such expansion of the biologist's world is continuing with the further exploitation of optical principles in the techniques of microscopy.

### Photosensitive Emulsion

Within the scope of my definition, the light-sensitive emulsion is an instrument, and photography has long been a versatile and effective tool of science, with applications in large number. The use of an astronomical telescope as a camera, permitting long exposures, rendered visible in a developed negative innumerable celestial objects not visible through direct viewing. Star images on a plate permitted accurate measurement of stellar positions and compilation of star atlases. Spectra of stars could be photographed, as could the Fraunhofer lines in the solar spectrum, for convenient astrophysical studies and for reference. For many years advances in astronomy depended largely on the light-sensitive emulsion on glass, the photographic dry plate. What made the photosensitive emulsion so valuable in astronomy renders it equally valuable wherever illumination is too low for direct vision, or where light outside the visible region can affect the emulsion, or where invisible energetic particles produce changes in halide grains which render them developable. Recent progress in raising the speed of black-and-white emulsions and in producing color film of high sensitivity has further increased the value of photography to science. Photomicrography has been of incalculable worth to the biologist, the chemist, the metallurgist, the petrographer—in fact to almost any scientist—by making permanent records of images with magnifications up to 2000 diameters. Beyond this the electron took over from the light waves and became the bridge, by way of the electron microscope and the electron-sensitive emulsion, to magnifications of several tens of thousands of diameters, and resolution of 10 to 20 angstrom units. Without the sensitized emulsion, the electron microscope would have remained a commonplace among instruments.

An important application of photosensitive emulsions is in sequence photography, in which time and position or configuration of transient phenomena are easily related. Only a generation ago one would have dismissed as fantastic the possibility of photographing elusive, evanescent events at a rate exceeding 4 million exposures per second, with good resolution and with intervals measured in millimicroseconds accurate to a fraction of a percent. With special cameras and with new sources of illumination of high intensity when the source is not self-luminous, such high speeds are routine. With special techniques, an increase to 40 million exposures per second is attainable, and the maximum speed is yet to be reached.

Replica of Hans and Zacharias Janssen's compound microscope, copied from the original. [Armed Forces Institute of Pathology, picture No. 53-662-1]

### Instruments Not Yet Conceived

Anyone must be greatly impressed if not overwhelmed by the increasing multitude of instruments for all conceivable purposes which have become so highly essential to both basic and technological research. There seems little left to invent or design. Yet the fact that it is difficult to conceive new approaches towards even more sophisticated instruments and systems does not imply that further progress is not to be expected. Indeed, the impact of a new instrument or system for measurement or for control is all the greater for its having been not easily foreseen.

The day is by no means past when science in amost any field will reach new levels by new methods and techniques in instrumentology. The events of the past several years attest to this: there neither can nor will be a sudden stop to progress in this activity. Without it there would be no space exploration, or, at the other extreme, fruitful research in nuclear physics. To warrant the efforts and costs pertaining to such enormous undertakings, the information must be factual, numerical, and hence specifically descriptive—information obtainable solely by means of instruments. And instruments not yet conceived will yield information not yet within our grasp, or at present imaginable.

The evidence for the indispensability of the instrument to the scientist's endeavors is clear and conclusive. In many cases he devises the instrument to satisfy his own immediate need; perhaps this is the normal pattern. But is this the only way by which new instruments are conceived, invented, and made available for scientific endeavor? Is there prospect of doing better than by the laissez-faire method? By "doing better" I mean doing away with the necessity for the scientist to devote untold hours to struggling with the instrumentation of his research, enabling him to spend those hours more fruitfully and directly on the work within his special competence. Is there possibility, therefore, of working out a division of labor by which the objectives might be reached more expeditiously? Such a possibility exists, I truly believe.

## Compartmentalization or Joint Attack

There is no novelty in saying that among the most productive fields of research are those where different sciences converge and overlap. There are such areas in which the problems challenge the interests and the joint effort of scientists from various disciplines. If the challenge is sufficiently compelling, it can draw together special knowledge and ability from different fields and unite them in an attack which any one scientist would not undertake by himself because of his lack of what others can supply. With their resources merged, the undertaking proves manageable. In such a team, one of the members would probably be a physicist or electrical engineer especially conversant with measurement and the associated experimental procedures. Such team research, notwithstanding its successful outcome when tried, is rare. If it is indeed fruitful, why are there not more examples of such accomplishment through cooperation?

The reasons are not difficult to discover. One lies in the tendency for departments in universities, and their faculty members, to isolate themselves in cozy self-sufficiency. The isolation, in the pattern of academic tradition and custom among scholars, raises high intellectual barriers among them. "Compartmentalized" is a descriptive word which has been aptly used. Another reason, and possibly a more fundamental one, derives from the scientist's compulsion to establish a record of achievement through written and oral publication. Unless he sees himself in a clearly defined, specialized field, he may have difficulty finding a publication that will accept his contributions, or a society before which he may give accounts of his works. If he cannot readily let the world perceive his professional qualities, his advancement in prestige and income is jeopardized.

Happily, small breaches are appearing in the walls of the compartments, and movements are developing through which good research will become known and recognized, whatever the content. Biophysics, for example, has come of age in the establishment of a national society and a journal, thereby giving biologists and physicists a two-way channel of communication. The trends in research, moreover, are towards team research on large projects and operations financed by the government, where the potential contributions from various sciences are needed. Members of teams thus engaged are drawn out of various compartments. With increasing recognition that their services are essential and consequently in growing demand, obstacles to individual advancement become less formidable.

Exploration of the feasibility of developing methods for such a joint attack on large problems, where instruments play a primary part, resulted a few years ago in *Publication No. 472* of the National Academy of Sciences–National Research Council. This is a report of the Biology Council entitled, "Instrumentation in Bio-Medical Research." In its hard-core approach to the life sciences through joint effort, it has given impetus to the trend toward abandonment of isolationism among biologists, medical research specialists, physicists, physical chemists, electrical engineers, and others and has indicated ways of bringing about the desirable distribution of effort. The report analyzes how such unified effort may materially strengthen the effectiveness of research in the biological and medical sciences. Answers are sought to such questions as: What can be done to advance the science of instrumentology and the art of instrumentation for greater service in fields where instruments might, in the past, have been more effectively used?

The general answers suggested by the Biology Council apply far more broadly than to biological and medical research alone. They apply wherever the problems are the concern of more than a single science. That some of the suggested solutions are feasible was demonstrated earlier in the work of the NAS–NRC Committee on Artificial Limbs, established in the mid-1940's, at first to study and improve limb prosthetics for amputees in the military services. The benefits of the work are today extending to civilian as well as military areas. It was begun and is continuing under committees in which biology, medicine, psychology, physics, chemistry, and engineering are in close cooperation. Both basic and applied research sponsored through the committees have contributed to the success of the program, in which, through engineering, research findings have been embodied in production designs.

Independently of these moves, the University Corporation for Atmospheric Research, in a comprehensive report of February 1959, proposed a plan with features similar to those in one of the Biology Council's recommendations. The report presents an outline for a National Center for Atmospheric Research, dedicated to "a search for the solutions of broad and fundamental problems of the atmosphere, with emphasis on those requiring extensive interdisciplinary participation." The nucleus of the Center would consist of the most competent research scientists that could be assembled from the various sciences. Its facilities, available to any qualified scientist, would include an instruments laboratory serving the other laboratories, well-equipped shops, and a working library. The Center would assist the scientists at universities in obtaining the use of large-scale research facilities, including instruments and systems, and would present opportunities for graduate students to engage in thesis research. The University Corporation has energetically moved to establish the Center, and funds have been allocated by the National Science Foundation for the initial steps, including the appointment of a director and his planning and organizing staff.

Other centers, both regional and national, devoted to major research endeavors, are under construction, such as Kitt Peak and Green Bank observatories. Still others will follow, like those designed to carry on the great research programs in oceanography recently proposed. The centers will not be hampered by barriers among sciences and departments, for their mission is to search out answers, not to maintain the straight lacing of straight-laced disciplines! They will provide freedom to communicate, and encouragement to cooperate, throughout their scientific staffs. In all of them, the common factor is dependence on instrumentation.

### Instruments, the Unifying Element

Little doubt remains that in our burgeoning activities, research in instrumentology and in instrumentation for research are gaining recognition and respectability. Paradoxical as it may be, the application of research to the furtherance of research is as basic as the research itself. Without it, much research would be vastly more difficult if not impossible. To illustrate: astrophysical studies depend on expert knowledge of the latest in lens design, on image converters, and on maximization of signal-to-noise ratio in microwave receivers; study of the atomic nucleus could not proceed without the application of research to the constant improvement of high-energy accelerators and on their proper design, construction, and management.

The scientist whose research deals with instruments for research is finding his place among his fellows. Since the scientist's reward is, in large part, recognition by scientists, this is important to science, for it will encourage able students to select an interesting and satisfying career. The trend is gratifying. More persons with unusual talent will be needed to assume the planning and execution of the experimental attack as the problems and the instruments for probing them become more involved and complex.

Science faces a bright future. So does man, in his enjoyment of the fruits of science, if he can become and remain a rational being in his relations with his fellow-occupants of this planet. Theory and experiment will continue, as they have in the past, to work hand-in-hand to advance knowledge, and the greatest advances will occur where self-centered and ingrown disciplines shed their isolationism and work cooperatively in exploring dark areas of broad interest. In all such efforts instruments, the indispensable tools of science, are the unifying element; hence they must and will play a vital part.

#### Note

1. I am greatly indebted for guidance, in my endeavor to appraise the notables in the light of modern historical research, to Dr. Duane H. D. Roller, associate professor of the history of science at the University of Oklahoma, Norman.

# Research on Handling Scientific Information

## Improvements in communication and information handling contribute to scientific progress.

Helen L. Brownson

Research on new and improved methods of handling scientific information received its initial impetus from an imaginative and stimulating article by Vannevar Bush entitled "As we may think," which appeared in *The Atlantic Monthly* in July 1945. He stated the scientific information problem succinctly:

"There is a growing mountain of research. But there is increased evidence that we are being bogged down today as specialization extends. The investigator is staggered by the findings and conclusions of thousands of other workers–conclusions which he cannot find time to grasp, much less to remember, as they appear. Yet specialization becomes increasingly necessary for progress, and the effort to bridge between disciplines is correspondingly superficial.

"The difficulty seems to be, not so much that we publish unduly in view of the extent and variety of present-day interests, but rather that publication has been extended far beyond our present ability to make real use of the record. The summation of human experience is being expanded at a prodigious rate, and the means we use for threading through the consequent maze to the momentarily important item is the same as was used in the days of square-rigged ships."

Bush predicted a change in this situation "as new and powerful instrumentalities come into use." He indicated tasks that might be performed by existing and potential mechanical aids in adding to the record of accumulated knowledge and in consulting that record. He envisaged a possible future device for individual use, a sort of mechanized private file and library, for which he coined the name "memex." Resembling a desk equipped with slanting translucent screens on which material could be projected for reading and a keyboard with selection buttons and levers, it could store on microfilm a tremendous volume of material—books, periodicals, newspapers, correspond-

The author is program director for documentation research in the Office of Science Information Service, National Science Foundation, Washington, D.C.