Instrumentation in Perspective

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THE TIME IS LONG SINCE PAST when any one man could know all contemporary science, and the time is almost past when a specialist in any one field can maintain acquaintance with even the high spots of many other fields. It might be assumed that the knowledge and interest of the specialist concerning the instruments and techniques used in building the structures of other sciences would be even more casual, fragmentary, and remote than his knowledge and interest concerning the final conclusions reached by those sciences, but this is not necessarily so. It is becoming generally recognized even by the most academic scientists, who are noting the more alert practices of their industrial colleagues, that many instruments and techniques developed for one particular field will find applications of equal or even greater importance in other quite unrelated fields. The astute experimentalist has therefore learned to keep his eyes open for advances in instrumentation wherever they may occur.

The remarkable development of measuring devices and techniques in the past two decades, following the logical implications of the concept of mass production, and the imperatives of automatic control of continuous processes, have supplied the scientific worker also with off-the-shelf equipment for measurement and control beyond the wildest dreams of an earlier generation, which had to spend much of its time in the design, fabrication, and repair of relatively crude measuring devices. Some understanding of the great variety of available instruments is essential to the modern scientist, not only to save his own time—for better concentration on his own particular research—but also to suggest new and fruitful lines of approach to his goals. Thus there is a very real and live interest in instrumentation on the part of scientists generally.

The scope and complexity of science and of technology are reflected in the overlapping of the various subjects that comprise the "field of instrumentation," making it difficult for the investigator to keep abreast of all the developments in instrumentation that are pertinent to his work, or to solve unaided the instrument problems incident to his goal, if he is at the same time to maintain a mastery in his own area of specialization. Thus it happens that experts in one or more of the various *types* of instruments have been more and more frequently called upon for advice and consultation, and the growing demand has encouraged a number of engineers and scientists to specialize in this phase of scientific work. In this work they have gone beyond familiarity with *instruments* and have concerned themselves also with the problems incident to the broader phases of instrumentation. They have familiarized themselves with the relationship between classes of instruments, the problems common to the design and application of all types of instruments, the analysis of instrument systems, and the theory and practice of applying measurement to the broad field of automatic control. In short, they have evolved the Science of Instrumentation. The specialists in this new science make their chief goal the improvement in the means whereby others may attain the ends of other fields of experimental science and technology.

The growth of this kind of specialization proceeded initially, and most rapidly, in industry. Chemical, electrical, and mechanical engineers acquired the title of "Instrument Engineers" and accepted the responsibility for selection, procurement, adaptation, and, frequently, for design and development of instruments for use in plant processes, as well as in plant laboratories.

A parallel evolution of specialists occurred in the instrument manufacturing industry, where engineers and physicists were essential not only for development design, but also for application (or sales) engineering. The intimate knowledge of industrial measurement problems gained by technically competent field representatives, working with the plant engineer or laboratory scientist to define needs, and with the manufacturers' design engineers to achieve a usable answer to those needs, has aided greatly in the rapid invention of practical, well-designed, and reliable devices for measurements of all types.

It is through academic research that fundamental problems have traditionally been solved, and the solutions first applied to new methods of measurement.

This continues, but usually the academic specialist in pure science is only secondarily concerned with exploring all the implications and applications of his discoveries in the broad field of measurement, whereas the engineer is generally concerned with measurements only in his particular field. Not until the past decade has it been widely recognized that the progress of science, as well as of technology, can be greatly accelerated by focusing specifically on the wider exploitation of existing techniques of measurement and on the improvement and development of new instruments and methods for measurement and control.

With a few noteworthy exceptions, university educators have been slow to provide their graduates with specific training relating to instruments, control systems, or the theory of measurement generally. Specialized education in the field of instrumentation, per se, has been primarily a matter of self-education, at least until recently.[1]

However, for those who sought familiarity with instruments and instrumentation there has always been a rich field of reference material available in all the sciences. For nearly twenty-five years two American periodicals have been devoted to the dissemination of information on instruments: *The Review of Scientific Instruments,* limited largely to research papers, and *Instruments,* the magazine of measurement and control, limited largely to descriptions of industrial instruments. Both these magazines have been effective media, not only for the dissemination of information on specific instruments, but also for the "propagation of the gospel" of increased productivity in science and industry through measurement and control. M. F. Behar, longtime editor of *Instruments,* was an early and leading proponent of this gospel and an exponent of the science of instrumentation, and this magazine is notable for its editorial emphasis on the important role of instrumentation and its even greater potentialities.

Abroad, the British *Journal of Scientific Instruments,* the German *Zeitschrift für Instrumentenkunde* and *Archiv für technischen Messen,* and the French *Revue de Metrologie* were the primary prewar journals dealing with instruments. Both in this country and abroad, however, many of the basic papers dealing with fundamentals of measurement, automatic control, transmission and recording of data, design of fine mechanisms, and development of general-purpose instruments continue to appear in other professional journals. The American Society of Mechanical Engineers has a notable record in this respect; its Industrial and Regulators Division was created to give greater recognition to this phase of mechanical engineering, and many significant papers have appeared in its publications. The American Institute of Electrical Engineers likewise has an active committee on instruments and measurements; and many of the activities of the Institute of Radio Engineers, as well as the papers in its journal, relate to instruments and measurements.

The *Proceedings of the Royal Society,* the *Philosophical Magazine,* the *Journal of the Optical Society of America, Industrial and Engineering Chemistry,* to cite only a few examples here and abroad, are fruitful references for papers on the general aspects of instrumentation. Various sectors of instrumentation are specifically encompassed and cultivated by other societies, such as American Microscopical Society, American Society for X-Ray Diffraction, the Electron Microscope Society, the Society for Experimental Stress Analysis, etc. One organization, the Instrument Society of America, founded in 1945 and having now about 4,000 members, devotes itself to the broad aspects of the art and science of instrumentation. The AAAS-Gordon Research Conferences sponsor a week-long session on instrumentation related to chemistry each year. The action of the editors of SCIENCE in devoting a special issue every year to instrumentation, indicates the growing recognition of the importance of instrumentation to science.

Like all of "science," the "science of instrumentation" may be recognized without being very exactly defined. It is not unique in this respect; most other branches of science are fuzzy at the edges; but, with no attempt at precision, we may characterize the field of instrumentation, first, by its relation to the other sciences; second, by its content; and, third, by its goals. In relation to other sciences, instrumentation is a horizontal field encompassing segments of practically all of them. This is well illustrated in an article by Waterfall and Hutchisson on "Organization of Physics in America" (*1*). In a chart showing the various vertical divisions of science, such as physics, chemistry, geology, biology, etc., and even their subdivisions, such as mechanics, sound, heat, light, metallurgy, surgery, physiology, etc., each field broken down by content, including one area called Instrumentation, the general field is presented as a horizontal division across all the sciences. This appears to be a useful and valid concept, and has led to the characterization

[1] The Massachusetts Institute of Technology and Columbia University have long offered instruction in automatic control, servomechanisms, instrument theory, etc. Many physics departments have given traditional courses in "physical measurements," and many engineering and science courses include much work on certain classes or types of instruments; but courses dealing broadly with the study of instruments are only now being added to university curricula. In this connection, a conference on "Instrumentation and the University," sponsored by the Instrument Society of America in 1945, helped to focus attention on the need for such training, with the result that many more institutions have since introduced courses in instrumentation.

of instrumentation as the common denominator of the sciences (*2*).

Just as the whole is often greater than the sum of its parts, so is the science of instrumentation greater than the sum of the individual phases of instrumentation that are inherent in the fields, for instance, of electricity, mechanics, electronics, optics, etc. It includes, besides the science of instrument design and application, the broad principles and general theories of measurement and control, and the operational analysis of the various steps in the handling and use of measurement data.

In the article by Condon (*3*), in the Annual Instruments Issue of SCIENCE on "Is There a Science of Instrumentation?" the question raised by the title was answered in the affirmative, with emphasis on the common elements in the problems, devices, and methods of measurement.

In another recent article, Trimmer (*4*) compares several views of instrumentation, without quite deciding whether it is a part of the newly introduced (and not-yet-quite-accepted) science of cybernetics named by Wiener. Wiener's book (*5*), subtitled *Control and Communication in the Animal and the Machine,* emphasizes the similarities between the methods of communications engineering and the physiological transmission of information by nerve action, and the probable benefits to each field that will result from intermixing the concepts and methods of each. It is certainly true that the problems of control are essentially the same for any living organism as for an automatic control instrument or instrument system. In both the animal and the instrument, stable control implies a "feedback" of output into the sensing element, and the principles of automatic control must be equally applicable to both. Having defined instrumentation as "the science of measurement and control," one might (with the permission of the communications engineers) include communication devices and theory, as well as automatic control. The domain of cybernetics then would appear to be instrumentation in the fields of psychology and physiology. However, we may leave to the future the decision as to whether cybernetics shall become an inclusive science, and, if so, whether instrumentation is a part of cybernetics or vice versa.

There is one other branch of science with which instrumentation is closely allied—so closely in fact, that instrumentation may be called the offspring of metrology. Some distinction may be made, however, between these fields, in the light of their differing emphasis. Metrology concerns itself not only with the devices of measurement but also with the carrying out of measurements and the compilation of data. Instrumentation puts prime emphasis on the development and application of the devices and techniques of measurement, and not so much on the continued utilization of the instrument for measuring purposes, or on the results of the measurements. Further, instrumentation apparently includes in its domain the important and expanding field of automatic control, and the theory of feedback of an instrument output to amplify that output by regenerative action, or to stabilize the output by negative reaction with the physical magnitude to be controlled. But it is fruitless to attempt too exact a definition of a subject that is so interwoven in others, and that is unique primarily on that account. Those parts of science generally which deal with instruments, with measurements, and with control combine to form the core of the science of instrumentation.

Looking broadly at all types of measurement, it is easy to see that there are several very distinct and separate parts, steps, or links involved in the complete measuring and control process. It is also easy to recognize that a number of common elements enter into the problems associated with all types of measurement.

1. First in the chain is, of course, *detection* or *response.* There are literally thousands of devices now available that detect or respond to some property, condition, or variation related to measurable magnitudes. Such "condition-responsive," detecting, or signal-generating elements, as they are variously called, have the common function of responding to the thing to be measured, with a resulting change in some other thing that can be measured. The generic term for such devices is *transducer,* which may, in its broadest sense, be defined as a device that responds to one physical entity, or change therein, by producing a change of some other condition, factor, or entity. A simple example is a mercury-in-glass thermometer, which responds to changes in condition—temperature—by changes in volume. To cite another illustration from the outer regions of our perhaps slightly stretched definition, a photographic plate that responds to light exposure by a change in the developable property of the emulsion may also constitute a transducer.

2. The second element is *transmission,* if the information is to be dealt with at a location remote from the point of measurement. A simple variant of the mercury-in-glass thermometer has an extremely long stem so that the movement of mercury in the capillary will be transmitted the requisite distance. Alternatively, the expansion of the mercury may change the amount of the metal in a stem surrounded by a coil, so that the electrical impedance of the circuit is changed; this change may be indicated at a distance. Or the expansion may move a flexible member to in-

terfere with the flow of gas through an orifice, and the resulting change in pressure may be transmitted through a pneumatic circuit.

In order to have a signal of sufficient strength for transmitting over long distances, or to operate indicating or recording devices, it is often necessary to add another step to the measurement process—namely, amplification. Any of these types of output may be further transformed into radio signals for still further transmission, leading into the entire field of radio telemetering.

3. *Indication* is a third factor which, in the primitive stages of measurement, was the end result. The pressure gauge, the electric meter, the visible fluid in the thermometer stem, are simple and familiar examples. The impact of psychology, physiology, and operational analysis may radically change the appearance and operation of the conventional needle-and-scale-type of indicating instrument. Digital representation of the measurement will probably be more and more frequently employed, leading to indicators like the ordinary automobile mileage indicator. The cathode-ray tube may be mentioned as a very convenient and versatile indicator wherein the scales and method of presentation may be varied at will.

4. Whether or not the result of the measurement is to be shown on an indicator, *recording* is often desirable, to make a temporary or permanent record of the measurement as a function of time or of some other parameter. The photographic recording of light beams reflected by moving coil galvanometers is one method of keeping track of rapidly changing measurements. The moving pen actuated by the measuring instrument or by a repeater, recording on circular or strip charts, is the commonest method of making records. A variety of repeater mechanisms has been developed for accurately, rapidly, and exactly positioning the pen in response to very slight signals, so that multirange recorders are now to be found in all laboratories. The recent development of means for storing information on magnetic wire or tape, which can eventually be erased and used again, has opened up new possibilities in this field.

5. When measurement information is obtained, transmitted, and indicated or recorded, it is logical to add *control* to the duties of the instrument, so that it may carry out the task of negotiating or doing those things the human operator would do if he noted the indication and followed the logical consequences dictated by the measurement. The output that operates the indicator or recorder is also compared with what is desired, and the difference between the actual and the desired, constituting an *error signal,* serves to set other devices in motion to change the thing which was measured. The simple household thermostat turns off the furnace when the temperature attains a certain value and turns it on again when the temperature falls below another certain value. The complex antiaircraft fire controller combines various measuring devices to determine height, range, direction, and velocity, and rate of change of course of the aircraft, computes the trajectory, allows for the characteristics and location of the gun, and sets in motion the controls to point the gun in the correct direction. Between these examples are a host of existing and potential devices and problems for automatic control.

6. Of a somewhat different character from the control procedure, the instrumental function of *data reduction and analysis* is also derived from the measuring action of instruments, through extension of the function to perform those steps that the human operator would take from logical consideration of the implications of measurement. An example is in the target scoring devices developed during the last war for gunnery training. Measurements were made of the direction in which the trainee pointed the gun when firing and were automatically correlated with the position of the simulated moving target on the screen. When the measurement fell within the moving range, a "hit" was automatically recorded and the number of hits totalized. In a more sophisticated device the average angle-of-miss could be measured and recorded for better training. In some cosmic ray studies the passage of a ray is in itself not a noteworthy event, but the statistical variation of the type and energy of the ray, perhaps only in its correlation with other variables, is significant. Here the primary measurements may be considerably distorted and simplified to reduce the problem of correlation to its simplest essentials. In this direction the development of devices for the automatic drawing of conclusions from data automatically sifted, sorted, reduced, and analyzed, is only in its infancy.

Since instruments are material entities, they are subject to ills arising from the idiosyncrasies of the material of which they are made, as well as those arising from the inevitable application of the third law of thermodynamics. Many of these elements may be grouped under one general heading as affecting accuracy: response characteristics, hysteresis, drift, repeatability, effect of overload. These effects may have a multiplicity of causes, such as friction and looseness in bearings, the misreading or dislocation of the pointer, the elastic defects in sensitive elements or supporting structures, changes in electrical, optical, or other properties of materials on which the performance depends, leakages, or instability of amplifiers, resistors, etc. Another class of problems relates not so much to accuracy as to physical characteristics desirable in instruments—compactness, portability, ruggedness, insensitivity to shocks and extremes of temperature, pressure, humidity, etc. Inasmuch as each successive factor in the instrument control cycle has its own shortcomings and defects, the struggle to maintain accuracy, reliability, repeatability, ruggedness, etc., is increased almost exponentially with the number of elements or links in the system. The many continuing problems, together with the stream of improvements being devised, and new materials being employed, promise a busy and fruitful future for the field of instrument engineering.

It would be an interesting but endless task to enumerate possible and expected developments in the many types and classes of instruments and control devices for general and special purposes. In a brief compass, only some of the general lines in which progress appears in the making may be listed.

1. It is easy to foresee an increased recognition for the science of instrumentation. Except for atomic energy, the development and application of instrumentation probably have greater potential material significance for our age and our civilization than any other factor on the contemporary scene. This seems valid militarily, industrially, and scientifically.

2. We may expect an accelerated trend toward educating scientists and technologists in instruments and instrumentation, so that within a few years accredited colleges of science and technology will have required survey courses in instrumentation for all undergraduates, as well as specialized courses on instruments in the specialized fields of engineering and science.

3. The foregoing factors will accelerate the present rapid rate of improvement in devices and materials, in methods and techniques for recording, transmission, especially telemetering, and in control systems, and in data reduction and analysis. Many of these improvements will probably result from intensive studies of the general factors in the control cycle which are entirely independent of the particular magnitude to be measured.

4. Extensive improvement in the classification of fields of instrumentation, of instruments, the uses of instruments, and the problems associated with instrument design and utilization is inevitable. More effective indexing, abstracting, and publication of information are assured in this field. Systematic surveys will be made of classes of instruments to determine their limitations and their potentialities and to extend their usefulness into other fields of measurement beyond those now being explored. Similar surveys of classes of measurement will help to indicate weaknesses in the design, construction, or operating principles of available instruments, and thus lead to intensive efforts for their improvement. Furthermore, systematic surveys of all physical principles useful for sensing, amplifying, recording, or for any other step in the measurement cycle will undoubtedly lead to a considerable increase in the already rich field of possibilities available to the instrument designer.

5. One may confidently predict also an increasing growth in the instrument industry, as both science and technology become even more dependent on large numbers of a large variety of instruments.

6. Finally, one may confidently anticipate an acceleration and continuation of the fruitful cross-fertilization of the various sciences that results from the development of instruments. One need only list a few of the instrumentally based fields that have, in the past decade, grown far beyond their modest beginnings to realize that this is only a start: spectrophotometry, mass spectrometry, microwave spectrometry, nuclear resonance techniques, radioactivity measurements, analogue computers and simulators, high-speed digital computers, magnetic recording, ultrasonics. Who can say what new instruments, and from them what new sciences, 1960 will see?

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