Is There a Science of Instrumentation?

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INSTRUMENTATION, as the word is used here, means the development and application of measuring devices which respond quantitatively to some physical property of a situation and give an output which depends on this property. The word instrument is often used in a broader sense, as when forceps are referred to as surgical instruments, but in this discussion it refers to measuring devices.

Nearly all of the progress of modern science and industry is directly traceable to the development and use of a wide variety of measuring instruments. With monotonous regularity people who discuss this subject quote Lord Kelvin's saying to the effect that one's knowledge of a subject is of a poor kind indeed unless one knows how to measure quantitatively the factors involved. Quoted often enough so that it now has the status of a cliché, this saying is nonetheless true.

With all this appreciation and understanding of the importance of measurement, the problem of devising suitable measuring instruments for use with different quantities and in different situations has, up until recent times, been left pretty much to individual scientific specialists to work out as best they can. But in recent years, especially in the past decade, it has come to be more and more widely recognized that the problems met in designing various kinds of instruments have a great deal in common. Because of the importance of these common elements there is a useful body of general doctrine and data which can be termed the science of instrumentation. Recognition of this fact has found expression, for example, in the founding and growth of the Instrument Society of America. The society is devoted to this over-all point of view on the design of measuring instruments—not on such an abstract philosophical basis that no particular results are attained, but rather in practical terms whereby the designer of an instrument for a particular purpose can derive maximum benefit from experience gained from other instruments which have been built, perhaps, for quite unrelated purposes.

This trend deserves to be more widely known and cultivated among scientists as a whole. Too often it happens that a man confronted with a measurement problem requiring instrumentation is such a specialist in the phenomena being studied that he is unacquainted with the mechanical, electrical, and optical design principles which enter into good design of his instrument and is impatient with them. He then works out a "gadget" to fill his needs as best he can and in many cases it depends greatly on the happy ingenuity of his machinist or glassblower. What the science of instrumentation is trying to do is to codify general principles and design data referring to instruments as a whole so that their design can itself be put on a scientific basis worthy of the scientific problems it is to help solve.

Instruments may be classified first as to whether the objects whose property is to be measured are discrete or continuous. For example, an instrument that measures the capacitance of a large number of small condensers, one by one, is measuring a discrete property, and one that indicates changing hydrostatic pressure is measuring a continuous property. Evidently all instruments of the discrete class have a great many problems in common with regard to the mechanism for feeding in the objects to be measured, independently of what quantity is measured, and the same is true of all instruments responsive to a continuous variable.

Of the instruments for discrete measurement, perhaps the simplest is that which merely counts the total number of events or objects to which it responds. In nuclear physics it has been necessary in recent years to develop electronic circuits capable of counting objects at very rapid rates. In these the object or event is made to give rise to an electrical pulse fed to a scaling circuit and eventually to a mechanical register. Such techniques will undoubtedly find application in many other fields, such as in counting blood cells in a blood sample and in automatic digital computing machines.

Second, an instrument can be classified as to the nature of the element in it which is sensitive to the quantity to be measured and the nature of the response made. Such a sensitive element is known generically as a *transducer,* since it changes a physical quantity of one kind into another. For example, temperature measuring devices are made which depend on (a) the differential expansion of two solids, producing elastic deformation of them, (b) differential expansion of a solid vessel and a contained liquid, producing relative motion, (c) change in electrical resistance producing an electrical output signal, and many others.

At first sight it may seem that the sensitive elements used for different quantities are so various as not to have much in common. If this were so there would be no general basis to the science of instrumentation. But it is not so. Every sensitive element gives some kind of output quantity Q (such as a linear motion to be observed visually or an electrical voltage to be dealt with appropriately in another part of the instrument). Let x be the physical quantity to be measured. It is a general characteristic of all responsive elements that they possess properties that need to be considered in design of an instrument independently of the physical nature of x and Q. Among these are (a) *sensitivity,* the quantity $Q'(x)$, giving the rate of change of output with change of input under steady equilibrium conditions, (b) *unsteadiness,* the measure of the fluctuation in output $(Q-Q_0)^2$ given by the transducer under a steady value of x due to looseness and erratic disturbances inherent in the situation, (c) *sluggishness,* the measure of the time rate at which Q assumes its new equilibrium value Q_1 from the value Q_0 when x abruptly changes from x_0 to x_1, and (d) *hysteresis,* which is a shortcoming of some transducers whereby Q is not dependent on x alone but on the past history of all values earlier assumed by x, and (e) *permanence,* the quality whereby $Q(x)$ retains its constant functional form over a long period of time whether the instrument is in use or not, thereby maintaining the instrument's calibration.

Evidently the design principles involved in specifying these characteristics of a transducer are quite general and will have similar limiting effects on the performance of the instrument no matter what the nature of Q and x. And as soon as we are past the transducer, evidently, we are dealing with the physical quantity Q instead of x. Hence from here on the design principles involved do not depend in any way on the physical nature of the quantity to be measured. In passing it may be remarked that sluggishness is not always an undesired element in a transducer, for sometimes the quantity which it is really sought to measure is not really variation of x at each instant, $x(t)$, but some sort of moving time average like

$$\bar{x}(t) = k\int_{-\infty}^{0} e^{-k(t-\tau)}\, x(\tau)\, d\tau$$

which is based essentially on the values of x in the past for a time of the order of $1/k$.

The next essential part of the over-all instrument may involve some sort of further transformation or amplification of the transducer output Q, as when the optical image of a linear movement is projected with enlargement on a screen, or when an electrical voltage is passed through a transformer. Evidently the design data for such devices will depend solely on Q, not at all on x, and therefore will be the same no matter in what branch of science or technology the instrument is to be applied.

The last part of the instrument involves the transformation of Q into some sort of indicating, recording, or control mechanism, depending on the use to be made of the data the instrument provides. Where indication is desired for individual readings or continuous observation, the coupling to the observer's sensory equipment is usually made through the sense of sight. Usually the indicating device involves the motion of a pointer relative to a scale, the position being noted visually by the observer. This led Eddington to regard all science as the systematization of relations between pointer readings obtained in various ways. This favored position of the sense of sight arises from its great sensitivity and resolving power. But one could also devise instruments in which, for example, the output, dependent on the quantity to be measured, controlled the pitch of a sound heard by the observer.

The transforming and amplifying elements of an instrument, as well as the indicating elements, need to be judged according to the same kind of qualities as were listed for transducers. In the over-all analysis there is nothing to be gained, for example, in having very little sluggishness in the transducer if the indicating element has much sluggishness.

A particularly simple kind of indication is that of the "go—no go" variety, which simply gives a signal if x is greater or less than preassigned limits or lies outside a preassigned range.

A recording mechanism is an element that gives a material record of the variation in x observed by the instrument. This is usually in the form either of a continuous curve drawn on a strip of paper or of a discrete series of digital numbers stamped on a strip. But it need not take either form and might be a magnetized tape with the output coded on in some way. Such a form would be applicable where some computing needs to be done on the output data by an automatic computer arranged to accept data on a magnetized tape as its input. The design considerations involved in a recording mechanism may be quite independent of the nature of the quantity x that is being measured.

Finally, a control mechanism is an element that takes the output, which may also be given presentation by an indicator or recorded in a recorder, and uses this to actuate some device in the original situation affecting the value of x. In the simplest case it is desired to have the control mechanism provide a situation which leads x to assume a constant value.

But it is only slightly more complicated to require that x follow some preassigned functional variation with time. Here all sorts of new problems present themselves, such as the tendency of the system to "hunt," that is, for the correction action brought into play by the control to produce greater effects than needed to bring x to the control value $f(t)$.

In more complex cases there may be more elaborate combinations of the basic instrument elements, as when several transducers respond to several quantities x_1, x_2 . . . and the signals so obtained are combined mathematically in some analogue or digital computer to produce one or several output quantities z_1, z_2 . . . which may actuate a control mechanism. Also it may happen that the output does not actuate a control mechanism related to the system being measured but actuates another device which maintains a prescribed relationship to that system. Thus, a gun director's input is optical or radar data about position of a target, but its output does not act directly on the target to control that position, but on a gun with the object of aiming it so as to launch a projectile which will hit the target.

Enough has been said to bring out the fact that in modern complex instruments a large part of the instrument is independent of the nature of the quantity to be measured. It is this fact that is giving rise to the recognition that there is a science of instrumentation concerned with these common elements and their systematic study and improvement. It seems quite likely that the instrument scientist will in the future play a role of steadily increasing importance in the development of all the sciences. It is a profession that should lend itself to specialization and workers in all fields should be relieved as much as possible from the distraction of having to devote too much attention to the detailed design of instruments for their particular needs.

In accord with these general ideas, the National Bureau of Standards is planning a program that will give just this kind of over-all study to the basic problems of instrumentation in all the physical sciences. Up to now, corresponding to the older and still common practice, instruments have not been considered from the general viewpoint, but separate and uncoordinated attention has been given to mechanical, optical, electrical, and electronic instruments in different parts of the organization. The program is being planned in cooperation with the Office of Naval Research and with research groups in the Army and the Air Force.

The objectives of this program are three: (1) systematic analysis of available methods and devices in terms of their precision and reliability; (2) studies of materials, components, and elements which are now known to impose serious limitations on instrumentation; and (3) development of specific instruments not now available.

Under the first heading, as part of the process of reviewing the literature, some particular limited field in which specific instrumentation problems are of interest will be studied. Careful analysis at this stage of how related measurement problems were solved in the past, of available related instrumentation, of its precision, and of the materials involved, will establish a basis for actual development work and provide critical data on the status of instrumentation in this field. Over a period of years, this approach should not only yield the concrete instruments needed—a need determined in this case by the cooperating agencies—but also accumulate information in a systematic manner, permitting a logical approach to subsequent problems.

Present demands for instrumentation improvement are essentially twofold: higher sensitivity and faster response. These are necessary because the time intervals with which present day work is concerned are extremely small, only minute displacements may be allowed, and the signals are low in power. In general, sensitivity can be increased if the time during which phenomenon is under observation is increased, but this often cannot be done because the existence of the phenomenon may be of short duration—as in, for example, nuclear and cosmic physics and in the study of biological cells. At the same time, noise level becomes a serious limiting factor where signals are weak.

In spite of these incompatible objectives, instrumentation is succeeding in extending sensitivity and signal response, but in the process large quantities of complex data are the result, creating the problem of processing such information. Here other instruments, whose functions are the orderly and integrated presentation of data, are needed. Recording devices are typical of this class of instruments, but more sophisticated types are necessary now for the analysis of large amounts of data, the performance of predetermined operations, and the presentation of the summarized findings, discarding unwanted background. Fortunately, machines like electronic digital computers, originally planned for solving mathematical equations, afford a means of attaining this end. Specific problems to be considered in the program of the National Bureau of Standards include transducers, electron optical field mapping, data transmission and reduction, improved microscopes, and so on. Work on some of these is already in progress. Coincidentally, the bureau's program in electronic digital computers is continuing: two machines are under construction in its laboratories in Washington and Los Angeles, while another five are being built by contract with private laboratories and industries.

One aspect of instrumentation, already mentioned, is the problem of materials and components. Related to this is the existence of principles of measurement whose application cannot be realized until developments in another field of science are achieved. Thus, electron optical field mapping represents an application of principles in optics to electronics, yet the realization of this important research tool had to wait until the science of electronics had advanced to its present state. An illustration of the dependence of instruments on materials is the wire strain gage. The principle was known as long ago as Ohm's law. Yet it was not until Simmons, Ruge, and De Forest developed methods of bonding the wire to paper and ways had been found to measure and record small changes in current that the principle was applied successfully. It is for these reasons that the study of materials and components, as well as the study of past methods proposed for measurement problems, is an integral part of the bureau's program.

The need for cross-channelling information in the sciences has grown acute in recent years. When it comes to instrumentation, this need has two aspects: basic developments in one field may provide the basis for instrumentation in another field and instruments developed in one field may have applications in others. As an illustration of the first aspect, scientists in the bureau's radio propagation laboratory recently developed and constructed an atomic clock which has remarkable precision. The heart of the development is the application of the knowledge of reasonance absorption in atomic physics and of microwave radiofrequencies to the problem of time. Again, the bureau has developed a standard of length based on the green line of mercury 198. This development depended on knowledge of atomic and nuclear physics, while the realization of the instrument and associated apparatus is a combination of knowledge in electronics and optics. An analogous story could be told about the recent measurement at the bureau of the magnetic moment of the proton. Here there is, at least in part, with excellent possibilities for full development in the future, the basis for atomic standards of the three basic measurements—time, length, and mass.

Indicative of the importance of cross-channelling information concerning instruments is the bureau's experience with diamonds as tools for measurement. Many years ago the bureau was interested in diamonds for ruling lines on precision scales, and devices and methods for cutting diamonds were successfully developed. The same group of scientists devised a diamond indentation method of hardness testing, which has been standardized and is used in the Tukon tester.

In the course of this work, scientists engaged in the study of aircraft cylinder wear, who had been using conventional measurement methods, recognized the possibility of determining cylinder wear by the change in length of a series of standard indentations, using diamond indentation. Modifications were needed, and a special instrument was developed capable of measuring wear to a precision of 0.00002 inch and of detecting even smaller amounts. Auxiliary developments continued in such fields as the cutting of diamonds and the drilling of small diamond dies for fine wire production.

These examples not only indicate the need for wide dissemination of information among the fields of science but reinforce the concept that instrumentation is a science in its own right. There is no reason why the practitioner of this science, conceived of as the logical approach to measurement problems, cannot provide measurement devices of a given type for a variety of fields. Certainly this would save the experimentalist much time and effort. Prior to this century, an analysis of the experimentalist's activity might have shown that the bulk of his time was spent in getting ideas and in analyzing the data of his subsequent experiments while a minimum of time was spent in the construction of instruments. In the present period, too often the scientific situation is such that the bulk of his time has to be spent in devising and constructing his instruments. From the point of view of research, this is unfortunate; and it is here that the science of instrumentation can make significant contributions not only to instrumentation as such but to the progress of original research.