humidity standard. In another project, the Office of Basic Instrumentation is studying the possibility of utilizing the hydrogen excitation spectrum for absolute humidity measurements at low temperatures.

Because the neutron has no electric charge, the measurement of neutron energies is a problem quite different from that of electron, proton, or alpha-particle energy measurements. Thus far, methods that have been employed for this purpose have been quite varied in principle. The work on neutron spectrometer evaluation will involve a summary of characteristics of neutron spectrometers now in existence and an evaluation of proposed designs for new types. The project on nucleonic instrumentation will be concerned with the development of fast memory tube-type pulse-height analyzers for nuclear research. It will also attempt to extend the use of memory tubes to other types of nuclear instrumentation. Another project in this field which is now being planned will include the construction and absolute calibration of a standard slow-neutron flux free of gamma rays and the development of instruments and techniques for intercomparison of unknown fluxes with this standard flux.

The projects described above, while not a complete listing, are typical and serve to indicate the scope of the work carried on by the NBS Office of Basic Instrumentation. Continual modification of the program and its objectives may be expected as the science of instrumentation develops and new instruments and measurement techniques become available.

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The Basis for a Science of Instrumentology[1]

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CHOICE OF WORDS can sometimes lead to confusion and misunderstanding. Under a title involving the word "instrumentology," I might well be expected not only to discuss instrumentology but even to know what the word means, particularly as contrasted with the more widely used term "instrumentation." Being unable to live up to these expectations, I shall make little use of either word, assuming only that in dealing with instrumentology it is proper to stay close to the concept of quantitative measurement.

We all do things we do not fully understand. Not every housewife who bakes a cake, even a highly successful cake, is well versed in organic chemistry and kinetic theory of gases. Nor do organic chemists themselves always understand *their* concoctions. Man has been measuring and controlling for a long time, and it is no derogatory reflection whatever on the usefulness of this activity to say that we still do not understand it as fully as we wish. Many good men have contributed toward a better general understanding of measurement and control—men such M. F. Behar (*1*), who has been closely identified with the applications, men who combine teaching and engineering, as does C. S. Draper (*2*), and men like the theoretical physicists Leo Szilard (*3*), John von Neumann (*4*), and David Bohm (*5*). In continuing to show today preoccupation with the task of reaching a better grasp of the fundamentals of the field, I wish to make forthright acknowledgment, first to those who by their infinitely varied, down-to-earth practical activities make the field, and make it the fascinating subject for speculation which it is, and second, to those who have contributed to such broader, more theoretical insight as we already have.

Measurement is an activity in which certain devices, instruments, are used. Let us look first at some of the terms reflecting (for example, in the Help Wanted columns) activities more or less closely related to measurement and control. Such activities are displayed in Table 1 in relation to the information concept. For the moment, at least, the words "information" and "thought" are used with the understanding that everybody knows their meanings but nobody can express these meanings in definitions. Since this has always been done with the word "time," we have in a double sense a time-honored precedent.

These activities are carried out both by human beings and by inanimate, or robot, devices. This has been emphasized by putting in the left-hand column terms characteristically applied to robot action and in the right-hand column terms characteristic of the human analogue. This kind of comparison between the human and robot analogues is of definite value in promoting understanding of both.

Now the two words which occur throughout this table are "information" and "thought." The close relation between the two can be illustrated by asking ourselves such a question as this: "Do we generate information when we get a new thought?" The arrangement in the table implies some difference between thought and information, since information is

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TABLE 1

ACTIVITIES RELATING TO INFORMATION

(Robot analogue) Activity	Information	Facility	(Human analogue) Result
Measurement	Generated	Instruments, senses	Thought ingredients
Control	Used	Control effectors, muscles	Deeds (thoughts in action)
Telemetering (communication)	Transmitted	Transmitters and receivers, senses and muscles	Words (thoughts in motion)
Recording	Stored	Memory	Thoughts at rest
Computing	Converted	Brain	Thoughts

shown as being generated in measurement and only "converted" (implying some kind of conservation law) in computing, whereas thoughts are generated in the "thinking process," the human analogue of computing, and the results of sense perception are listed only as "thought-ingredients."

Since the information concept appears throughout Table 1, it seems reasonable to call the field represented by the complete table "information theory." Now we may ask what other similarly broad terms mean in relation to this table. For example, quality control is a rapidly emerging field, already complete with professional society and professional journal. As I see it, quality control is just a special case of control, in which the emphasis is on various features of some product of a process, rather than on a physical variable characteristic of the process itself. Process control is the term usually applied to control of these variables. Together (and indeed with some degree of overlap) process control and quality control make up the total item listed in Table 1, which may therefore be more fully described as process-quality control.

Operations research is another burgeoning field which seems related to our topic. As I understand it, operations research is the effort to apply to various purposeful human activities any relevant scientific knowledge, any useful mathematical techniques (notably, probability theory), and even common sense. So far as I am aware, operations research has as yet no clearly established structure of its own.

To show something of the possible relations between operations research and information theory,

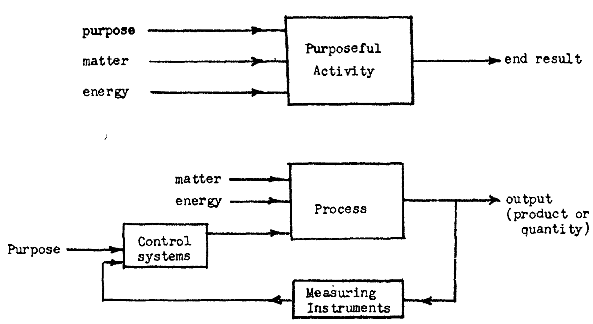


FIG. 1. Comparison of operations research and control.

Fig. 1 compares a general picture of any purposeful activity and a diagram of the more special purposeful activity we call process-quality control. Now if the more general diagram accurately portrays the subject matter of operations research, then control seems to be a subtopic of this discipline. Before accepting this conclusion, however, we should consider the difference between the block diagram of an activity and the block diagram of a system. System implies more or less permanent structure, especially material structure, typified by the aggregates of hardware constituting many physical systems. Activity implies function, interaction of matter and energy, with more emphasis on change and less on static structure. By adopting the viewpoint of the quantum physicist, one can say that system theory eventually dominates. For by sufficiently enlarging the definition of the system (in the limit, if necessary, to include the entire universe), any activity can be described in terms of possible states of the system and transitions between these states.

For those like ourselves who are primarily concerned with aggregates of hardware, the viewpoint of system theory is more immediately useful. But before leaving the subject of operations research, we should notice the important role in it of processes of measurement and observation. The original military work on operations research was based very largely on observations of the actual effectiveness of various military devices. This observation in the field constituted a feedback link very similar to the measuring instruments in our control diagram.

System theory might be called the theory of block diagrams, if we use the blocks primarily to represent more or less permanent physical aggregates, rather than functions or activities. As an example, in the block diagram of control in Fig. 1 each of the three blocks stands for a physically separate or separable aggregate of matter. As regards the general pattern of such diagrams, it is my opinion that the feedback pattern is not in any sense basic to the general theory of block diagrams i.e., to general system theory. The feedback pattern is just one pattern that may show on a block diagram. Its widespread occurrence in biological and physical systems gives it a great practical importance, which should not however be confused with logical importance. (For an opposite opinion, see Ashby [*6*]). On any block diagram the blocks represent minor systems, the lines represent interaction (flow of matter or energy) between minor systems, and the total pattern of blocks and lines can be regarded as a major system. Information theory is largely the theory of "lines between blocks." Feedback theory becomes one subtopic under "patterns of interaction among systems."

The flow along the lines of a block diagram may represent flow of matter or of energy. The use of a line also to show the input of purpose may perhaps raise some questions. Whether or not "purpose" is a good generic word with which to label such things as set-point input to a controller, I have for the moment simply wished to emphasize what I consider to be the distinctive character of this type of input.

We might try to characterize these flows in terms of three "dimensions" of mass, energy, and information, as suggested by the arrangement shown in Fig. 2. Each of the examples of flow is actually three-

	Matter Flow	Energy Flow	Purpose Flow
Mass	Sand conveyor	Steam pipes	Bullets
Energy	Steam pipes	Electrical power lines	A-bombs
Information	Letter mail	Telephone lines	Propaganda

FIG. 2. Dimensioning of flow lines.

dimensional, since all involve some displacement of mass, of energy, and of information. The vertical position assigned is an indication of the principal dimension of each example.

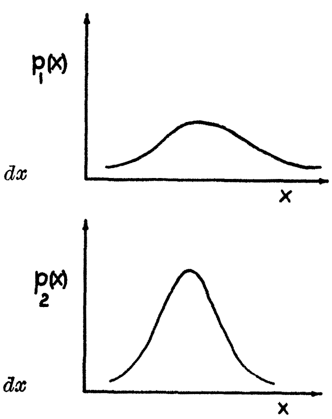
A further exercise in what may be called dimensioning of flow lines would be to consider four conveyor lines in a plant, one carrying crude, unprocessed ore, another carrying highly purified graphite, a third carrying rough castings of a machine part, and the fourth carrying the same parts precisely finished. Here we have four lines of matter flow which might conceivably be identical in mass flow rate. What is carried by the graphite that is missing in the flow of ore? Chemical thermodynamics can furnish a tolerably complete answer in terms of energy and entropy, and negative entropy may be correlated with information (*7*). The difference between the finished and unfinished machine parts is more subtle. The problem is one of associating quantity of information with structure—a problem which has not been solved so far as I know, and which is worthy of further attention and effort. It is basic to such types of measurement, for instance, as autoradiography (*8*).

If we turn now from these broad considerations of the fields of information theory and system theory, we may look for a suitable point on which to concentrate more detailed scrutiny. I think it is the concept of measurement which should get the spotlight, since it is the central concept of instrumentology, and since in it information seems to originate.

The verb "to measure" has two well-established meanings. I shall illustrate them by referring to a grocer waiting on a customer. The customer picks out a watermelon he wishes to buy, and since the grocer sells it by the pound the melon must be weighed. Such a process I shall refer to by the hyphenated term "measure-estimation," since the purpose is to measure (in the sense of estimate) the unknown weight of the melon. Suppose next that the customer asks for five pounds of sugar, which the grocer keeps in bulk in a barrel. To meet this situation the grocer must measure five pounds of sugar, using no doubt the same scales on which he weighed the melon. But this is a fundamentally different process, which I shall call measure-establishment, since this measuring is, in the sense of "measuring out" or "measuring off," the establishment of a known magnitude chosen a priori by the customer.

Measure-estimation is what is now commonly called measurement, and measure-establishment is now commonly called control. The sugar-weighing is the prototype of all our measured, controlled modification of structure, such as precision machine work; of our controlled modification of chemical composition, such as ore processing; of our controlled manipulation of various forms of energy, as in temperature control. Yet in the prototype examples of the grocery store the only significant difference between measure-estimation and measure-establishment seems to be that in one case the customer's initiative was directed to an object (a particular melon) and in the other case to a particular numerical quantity (five pounds).

The results of the two weighings are the same in that in each case a certain magnitude is known, and, assuming the same scales and equally careful manipulation, known to the same accuracy. The a priori situations, however, are different—the melon weight was unknown, the sugar weight was as definite before as



$I_1 = \int p_1(x) \log_2 p_1(x)\,dx$

$I_2 = \int p_2(x) \log_2 p_2(x)\,dx$

$\Delta I = I_2 - I_1$

FIG. 3. Information generated in measurement.

after. In the sugar-weighing, something was done; but in the melon-weighing, something was learned. Now comes an essential question: how much was learned? how much information was generated?

Norbert Wiener (*9*) proposes a method for quantitatively specifying the amount of information gained in a measurement. His suggestion may be explained by reference to Fig. 3. Assuming a continuously variable quantity x is being measured, the probability density estimated for x before the measurement is p_1, and after the measurement one has a sharper distribution p_2. Then the information gain is the difference of the two integrals $I_2 - I_1$. There would be a corresponding definition for a discrete variable. Wiener's suggestion seems perfectly workable, provided one can realize the two functions p_1 and p_2. The a posteriori distribution p_2, especially when based on more than one or two observations, can doubtless be taken as a normal distribution with specified mean and specified probable error. But the a priori function p_1 seems difficult to assess, especially when it must be based on only very scanty knowledge. One always has some a priori information, but it is seldom easy to put this estimate in quantitative form.

Let us turn now from the *process* of measurement to the *devices* used—that is, to instruments. We are, of course, studying one problem, whether we phrase it as the study of the device as used in the process or the study of the process as carried out with the help of the device. The choice is one of perspective and emphasis. Looking especially at instruments with a view to classifying (*10*) and specifying them, one is confronted with some questions which are easy and others which are hard to answer. For example, I think it is easy to specify for most instruments the instrument's class, that is, the variable it helps to measure; the instrument's accuracy; its scale range; and its frequency range or its time constants. But there is another important quality of an instrument which in many cases can hardly be given a numerical value.

This is the interaction of the instrument with the system on which it is used. I have designated this quality of an instrument, its efficiency (*11*). Figure 4

measured quantity	efficiency related to:	
property of matter	size of sample change of sample	changes in remainder of universe
form of energy	energy interchange with system	

Fig. 4. Factors in instrument efficiency.

displays some of the factors entering into this concept. The two basic types of measured variables are shown as properties of matter, including chemical composition along with the various mechanical, thermal, electrical, and optical properties; and energy components, such as force, temperature, or voltage. For property measurement an efficient instrument would require only a small sample of matter, and would not change it appreciably (e.g., it would be a "non-destructive" test). For energy component measurement, high instrument efficiency would be reflected primarily in small energy interchange with the system on which the measurement is made—i.e., to which the instrument is coupled. For both types of variables there are other, more peripheral considerations which seem to be related to efficiency. In Fig. 4, these are designated "changes in the remainder of the universe." Thus an instrument which required exorbitant auxiliary power, or one which emitted dense clouds of acrid smoke, or one which weighed several tons, would be in some sense inefficient. It is not clear what role, if any, should be assigned to these peripheral factors in our specification of efficiency.

The most definite central portion of this efficiency concept is the interchanged energy. In this domain it seems reasonable to define efficiency as the ratio of reading to energy exchanged (see Fig. 5). For ex-

$$\frac{\text{voltage}}{\text{power}} = \frac{\text{voltage}}{\text{current}} \qquad \frac{1}{\text{voltage}} = \frac{\text{impedance}}{\text{voltage}} \qquad \left(\frac{\text{ohms}}{\text{volt}}\right)$$

$$\frac{\text{current}}{\text{power}} = \frac{\text{current}}{\text{voltage}} \qquad \frac{1}{\text{current}} = \frac{\text{admittance}}{\text{current}} \qquad \left(\frac{\text{mhos}}{\text{ampere}}\right)$$

$$\frac{q}{\text{power}} = \frac{q}{q^*} \qquad \frac{1}{q} = \frac{\text{immittance}}{q}$$

Fig. 5. Efficiency of energy-measuring instruments.

ample, a voltmeter's efficiency would be a ratio of voltage to power. This corresponds to the customary specification of ohms per volt. The corresponding specification for an ammeter would be mhos per ampere. In general, if an instrument measures an energy-component quantity q, efficiency would be the ratio of q to power, or if we define in each case a suitable immittance, of immittance to q. It would doubtless be wise to stick to the convention, observed with voltmeters, of using the full-scale reading as the defining value.

Whatever may be the practical appeal of this usage, it has a fundamental logical importance in denoting the work done *on* the instrument, or the energy input. There is also work done *by* the instrument in making the information known. In many cases this work appears in the rotation of a pointer against a torsional spring. The way in which this "output work," as reflected in sensitivity, may have to be compromised with "input work," as reflected in efficiency, is illustrated in Fig. 6. Here we consider an ammeter of the moving-coil, permanent-magnet type which is carrying a current I sufficient to deflect it through the full-scale angle A. The deflecting torque is the product of this

torque	$SA = BlaI$
efficiency	$e = 1/RI$
for narrow coil	$l \cong cR$
resultant equation	$Ae = \dfrac{Bac}{S}$

Fig. 6. Compromise of sensitivity and efficiency in an electrical meter.

angle with the torsional spring stiffness S. The torque is also given as product of current with magnetic induction B, length of wire l, and radius of coil a. The efficiency e, neglecting reactive impedance, is inversely proportional to coil resistance and to current. For a long narrow coil, the length of wire cutting the magnetic lines is nearly equal to cR, where c is conductivity multiplied by cross-section area of wire in the coil. Combination of these relations shows that full-scale angle and efficiency are inversely proportional to each other. In the proportionality constant, the factor a/S is directly related to the time constant of the movement, and hence to its accuracy in following changes. Thus we have here a simple illustration of the general situation, that accuracy, range, and efficiency are competitive factors of merit which must always be compromised in any given design.

In effecting this compromise in design, it would help to have a more definite picture of the relation of information output, reflected in range and accuracy, to the output work required by various methods of indication. During the past year I have been interested, as part of an ONR-sponsored research (*12*), in comparing the common pointer-scale combination with other indicating means. Though it does not seem possible to summarize quantitatively the many factors, some objective, some subjective, entering into such a comparison, I must say that the pointer-scale method stands the comparison very well.

My general thesis has been that the science of instrumentology must be advanced by clarifying the *activities* and *processes* of measurement and control, both in their essence and in their relation to other activities and processes; and by clarifying and organizing our understanding of the *devices* used in these activities. The specific aspects of these two broad objectives which I have touched upon are, of course, only a few of the many interesting questions calling for solution.

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Into a New Century

THE YEAR 1953 marks the one-hundredth anniversary of the Bausch & Lomb Optical Co. At this milestone the company's pride in its achievements is tempered by the challenge of the future. To that future it dedicates its centennial.

Among those who joined the exodus from Europe in 1849 was John Jacob Bausch, founder of the Bausch & Lomb Optical Co. Arriving in New York, he traveled westward to Buffalo where he worked as a cook's helper and carpenter for several months, then borrowed five dollars, and went to Rochester. There he eventually opened the little optical shop that was destined to become one of the world's leading producers of optical glass, scientific instruments, and ophthalmic products.

If John Jacob Bausch had not lost two fingers in a buzz saw accident in 1852, America might never have been the beneficiary of a company which revolutionized the optical industry and provided some of the critically short materials and instruments necessary to win two world wars. After the accident, Bausch found it necessary to continue part-time work at his trade of woodturning for a year, but the real birth of the world-renowned firm, 100 years ago at Rochester, can be traced to that fateful event. It brought the young German immigrant into contact with a fellow immigrant, Henry Lomb, who had collected twenty-eight dollars for his friend to tide him over his convalescence. When Bausch opened his first optical shop, in 1853, it was with the help of sixty dollars borrowed from this same friend. Bausch demonstrated his sincere appreciation by making Lomb a full partner in the struggling business that same year. In 1868, Lomb entered the Union Army and served as a captain in the 13th regiment, New York Volunteers. He sent home his soldier's pay to keep the small business alive. Neither partner, during their long years of association, found it necessary to have a contract with the other—a notable example of faith and mutual trust.

Like most other beginning enterprises, the young business was beset by many difficulties. The first real promise of success came with the development, by Bausch, of a spectacle frame made of hard rubber. The kitchen range in his home served as shop laboratory for this first "plastic" eyewear. From this, the little shop became a successful manufacturing enterprise. Previous to this development, the only plastic