and cover so wide a range as to make the outsider doubt their validity on a priori grounds. May I remind you that about ten years ago the Lexington Project predicted that the cost of the nuclear-powered aircraft would be 1×10^9 and the time required, ten years. As it turned out, after ten years and an expenditure of 1×10^9, we have words, not nuclear airplanes, flying. Just because a project is very big and very expensive does not mean that the project will be very successful.

The other main contender for the position of Number One Event in the scientific Olympics is high-energy physics. It, too, is wonderfully expensive (the Stanford linear accelerator is expected to cost 100×10^6), and we may expect to spend 400×10^6 per year on this area of research by 1970. The issues with which such research deals have greater scientific validity than those dealt with in the *manned* space program, but its remoteness from human affairs is equally great. It has the advantage, from our point of view, that we are ahead of the Russians in high-energy physics.

But even if it were possible to generate around high-energy physics the same popular interest that arises naturally in connection with manned space travel, I am not persuaded that this is the battleground of choice. I personally would much rather choose scientific issues which have more bearing on the world that is part of man's everyday environment, and more bearing on man's welfare, than have either high-energy physics or manned space travel.

There are several such areas, and we are generally very far ahead in them. The most spectacular is molecular biology—a field in which the contribution from the East is minimal. We have learned more about the essential life processes—growth, protein synthesis, and reproduction—during the past decade than during all previous history. In my opinion the probability of our synthesizing living material from nonliving before the end of the century is of the same order as the probability of our making a successful manned round trip to the planets. I suspect that most Americans would prefer to belong to the society which first gave the world a cure for cancer than to the society which put the first astronaut on Mars.

I mention also the group of economic-technical problems which arise from the increasing pressure of population on resources. Of these, nuclear energy is the best known. Here the Western lead is clear, and it is important to consolidate the lead. There are others—the problem of water, or atmospheric pollution, or of chemical contamination of the biosphere, for example. Each of these is a technical issue which can lay claim to our resources—a claim that will have to be heard when we make choices.

But it is presumptuous for me to urge that we study biology on earth rather than biology in space, or physics in the nuclear binding-energy region, with its clear practical applications and its strong bearing on the rest of science, rather than physics in the Bev region, with its absence of practical applications and its very slight bearing on the rest of science. What I am urging is that these choices have become matters of high national policy. We cannot allow our over-all science strategy, when it involves such large sums, to be settled by default, or to be pre-empted by the group with the most skillful publicity department. We should have extensive debate on these over-all questions of scientific choice; we should make a choice, explain it, and then have the courage to stick to a course arrived at rationally.

In making our choices we should remember the experiences of other civilizations. Those cultures which have devoted too much of their talent to monuments which had nothing to do with the real issues of human well-being have usually fallen upon bad days: history tells us that the French Revolution was the bitter fruit of Versailles, and that the Roman Colosseum helped not at all in staving off the barbarians. So it is for us to learn well these lessons of history: we must not allow ourselves, by short-sighted seeking after fragile monuments of Big Science, to be diverted from our real purpose, which is the enriching and broadening of human life.

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CURRENT PROBLEMS IN RESEARCH

Ice Alloys

For arctic operations ice and snow can be improved as structural materials by appropriate alloying.

W. D. Kingery

Ice and snow have been used as construction materials by indigenous arctic peoples for a long time. Applications of ice include roads, bridges, and staging areas for logging operations; snow has been used for houses. In each of these uses the properties required of the material are not stringent, and the builders have used, by and large, the natural, unimproved materials.

More recently, extensive progress has been made by the U.S. Army in developing methods of excavating tunnels and constructing chambers in glacial ice and snow. Similarly, compacted snow areas were used as roads and parking areas for thousands of automobiles during the 1960 Winter Olympics at Squaw Valley, California, and compacted snow roads and ice runways for aircraft have been used during IGY activities in Antarctica (*1*). In such construction, the physical properties of the material used determines to a large extent the operational capabilities of the product. Present limitations on the use of ice and snow as structural materials are of two kinds: (i) the engineering properties of ice and snow in the natural state are rather poor; (ii) improved processing techniques are needed for forming the raw materials into useful shapes. The present discussion is limited to consideration of

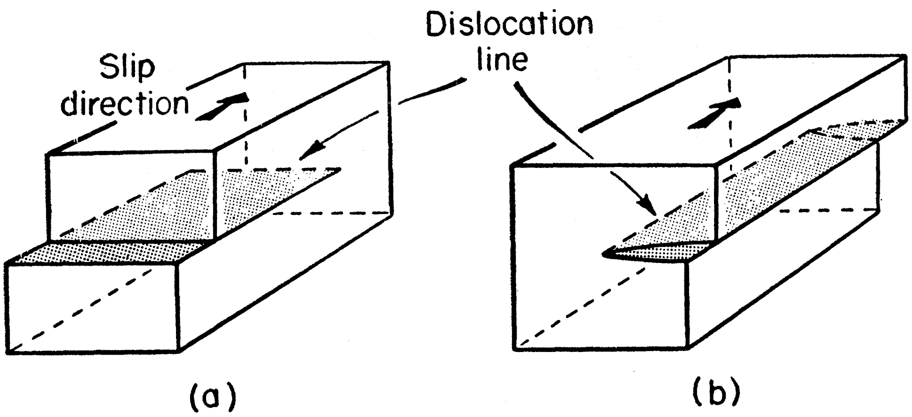

Fig. 1. Dislocation in crystal structure is a line imperfection which separates the part of the crystal that has slipped by plastic deformation from the portion that has not slipped. The line can be (i) normal to the direction of deformation (*a*); (ii) an edge dislocation; (iii) parallel to the direction of deformation (*b*); (iv) a screw dislocation; or (v) a combination of these.

properties of the material, and, in particular, of ways to improve the natural materials.

Since arctic areas, along with the oceans, remain the earth's great unexploited frontier, development of new construction materials and new understanding of the behavior of naturally abundant materials under natural and artificial conditions are also of great importance. In the past, and perhaps at present, most arctic and glaciological research has consisted of observation, exploration, and mapping, but scientists are now taking a more quantitative approach in explaining and systematizing observations of natural phenomena. In recent years, efforts have been made to develop ice alloys in much the same way that metallurgical alloys, superior to metals found in nature, were developed (*2*).

To date, the most extensive effort to utilize ice and snow as a structural material was the British attempt to design and construct aircraft carriers of ice during World War II (*3*). This effort was conceived as a possible solution to the desperate problem of extending the air cover beyond that provided by airplanes based on the British Isles in 1942. Various suggestions for using natural materials, such as icebergs or arctic ice floes, proved to be impractical, and a serious effort was made to find an ice structure which would be more useful. This resulted in the development of an ice-sawdust mixture, which was named "pykrete." This product was stronger than natural ice and of more uniform properties, and it provided the basis for a program of aircraft-carrier design. The exigencies of the war situation changed, however, and this project was never carried to completion.

In planning the development of other ice alloys it was essential to consider the sources of strength in various materials. Such investigations have been most thoroughly documented in regard to metals. One objective of the work under discussion has been to determine just how many of these findings are paralleled in a new base material such as ice.

Origin of Strength at Low Temperatures

The basis for understanding the strength behavior of most metallurgical alloys at low temperatures is the successful application, in recent years, of dislocation theory (*4–6*). In metals, dislocations or line imperfections (the line is the boundary which separates a region over which deformation has taken place from the region where deformation has not yet occurred) lead to plastic deformation, as shown in Fig. 1. Strengthening is accomplished by eliminating dislocations or by preventing a dislocation from moving along in its slip plane. Such motion can be prevented or reduced by introducing impurities into the structure, which tend to concentrate at dislocation sites and prevent motion; or by adding a second component that gives an ordered structure, so that the work required to move a dislocation is increased; or by prior deformation (cold work), which introduces enough new dislocations in the structure to make it difficult for those already present to move. A second general method of increasing strength consists of the addition, as a second phase, of hard particles which tend to key the slip plane on which deformation occurs and thereby increase the stress necessary for deformation.

In contrast to the yield strength that characterizes the plastic deformation of metals, in ceramics brittle fracture occurs with negligible plastic deformation. The causes of fracture in different materials have not been critically defined, but various processes can lead to the formation of small cracks. At the tip of each crack, stress concentration leads to high local stresses and ultimate fracture. The Griffith criterion for fracture is that the strain energy released by crack propagation is equal to the surface energy of the new surfaces formed. This criterion is met even when slight plastic deformation occurs at the tip of the crack; in that case allowance is made for the energy-absorbing process by use of the phrase "apparent surface energy" (*6, 7*). The causes of microcracks or Griffith flaws, which act as stress concentrators, are varied. With the exception of prior deformation, the most common cause is surface abrasion, particularly for glass and ceramics. It is well known, for example, that the fracture strength of glass is above 1 million pounds per square inch if the surface is carefully protected; strength of about 10,000 pounds per square inch is usual.

Origin of Strength at High Temperatures

At high temperatures, a new element is introduced into the strength behavior of all materials. This results from increased atomic mobility; dislocations in the crystal are no longer restricted to one crystallographic plane but can shift to an adjacent plane by a process called dislocation "climb." This greater freedom makes it easier for dislocations to be freed from concentrations of impurities or from blocking particles in their path. As a result, extensive deformation can occur prior to fracture; creep, or a pseudoviscous behavior, is observed. On annealing at high temperatures, any dislocations present tend to line up in positions of low energy, as shown in Fig. 2.

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The increased atomic mobility at high temperatures greatly reduces the effectiveness of solid solution, ordered structures, and prior deformation as strengthening techniques. The method which remains most suitable is that of adding hard particles as a second phase which restricts dislocation motion. This restriction does not completely eliminate dislocation mobility and deformation, since dislocations can climb out of their normal slip planes and so circumvent a restricting particle. In metallurgical processing a second serious problem exists; adding hardening particles of fine particle size is best accomplished through precipitation reactions, but the particles tend to go into solution at high temperatures. This has led to new techniques in the development of metallurgical alloys—techniques in which dispersion-hardened alloys prepared by mixing in the hard particles are used, rather than heat-treated, precipitation-hardened materials.

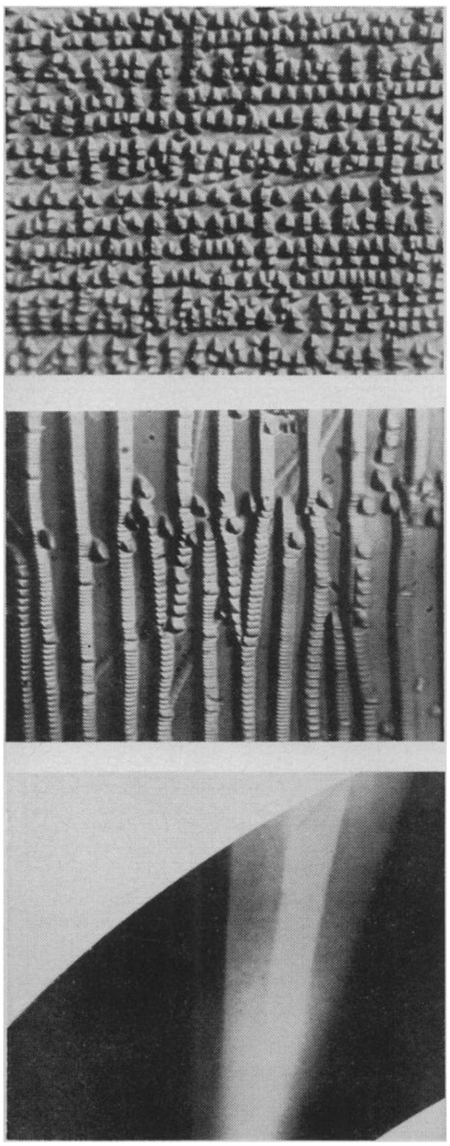

Fig. 2. (Top) The ends of dislocations are marked by etch pits in a crystal of Al_2O_3 which has been deformed. (Middle) At high temperatures these dislocations are mobile and line up in polygon boundaries. (Bottom) Polygons separated by these boundaries are visible in polarized light. These same phenomena are also observed in deformed ice. [Peter Gibbs, department of physics, University of Utah; after W. D. Kingery, *Introduction to Ceramics* (Wiley, New York, 1960)]

A high-temperature strengthening method which has been discussed for metallurgical alloys but is employed mainly for soft materials such as plastics is the addition of fibers rather than particles as reinforcement. In order for such reinforcements to be effective in preventing fracture, the fiber must (i) be much stronger than the matrix material and (ii) have a much higher modulus of elasticity, so that most of the applied stress is carried by the reinforcing material rather than by the soft, deformable matrix. This kind of reinforcement is effective only over a temperature range within which there is a wide difference between both the strength and the deformation characteristics of matrix and fiber. This is the case when the reinforcing additive at low relative temperature (low with respect to its own properties) is dispersed in a matrix material which is at a high relative temperature.

Development of Ice Alloys

Principles. For success in the development of ice alloys, it is necessary to have good information on the properties of ice and on its behavior with regard to deformation and fracture. Fortunately, many such investigations have been made, and the deformation and fracture behavior have been carefully observed. In general, ice is similar to other materials in these respects; it is particularly closely related to sapphire (Al_2O_3), to which it is similar in crystallographic structure. Aluminum oxide, like glass, fails with brittle fracture at low temperatures, but at high temperatures in an oxyacetylene flame, deformation occurs, and a rod of material can easily be bent (Fig. 3). If the rod is suddenly pulled apart instead of being slowly deformed, brittle fracture results, even near the melting point. In aluminum oxide, these characteristics have been related to the crystal structure and the kinds of dislocations which it is possible to introduce (*8*). Slip deformation in aluminum oxide always takes place along the basal plane of the hexagonal structure.

Table 1. Strength of fresh ice with sawdust and Fiberglas, respectively, added.

Addition (%)	Modulus of rupture (kg/cm²)	
	Sawdust (−17°C)	Fiberglas (−20°C)
0	22.5	24.1
0.8	22.7	24.0
2.5	35	65.4
9.0	60	161
14.0	66.7	

Ice has hexagonal symmetry—a fact well known to anyone who has seen a snowflake—and the structure can be considered to consist of stacked layers. At high temperatures, when slowly deformed, these layers tend to slip over one another like a pack of cards, and deformation readily occurs. At high rates of deformation, however, brittle fracture occurs; the moving dislocations are apparently unable to achieve a sufficiently high velocity or rate of multiplication to keep up with a quickly applied load. As the temperature is lowered, the rate of deformation is sharply reduced, and brittle fracture occurs even when loads are applied more slowly. However, deformation occurs when the load is static or applied slowly, even at temperatures of −40°C, and fracture does not occur immediately. Observations of different strengths and deformation characteristics for different loading rates (the viscoelastic characteristics of ice) have led to some confusion in the literature. Nevertheless, it is clear that ice behaves like a material deformable at high temperature and tends to flow under an applied stress when used for structural purposes where loads must be carried for significant periods. As a result, the kinds of alloys which may be developed are those characteristic of high-temperature systems.

One result of these findings on the effect of temperature is the demonstration that alloying additives in solution (few materials are soluble in ice anyway) cannot be expected to produce useful alloys under the "high-temperature" conditions essential for the development of proper alloys. As found from long experience with metals, plastics, and ceramics, the kinds of alloys which are most useful under these conditions are those made with stable second-phase additives having useful properties. Three different kinds of additives have been tried: (i) dispersed particulate material of high elastic modulus and high strength; (ii) fibrous material having good ductility and moderate strength; and (iii) fibrous material having high elastic modulus and high strength. Combination of these materials and sophisticated development of particular compositions have not been attempted.

Dispersed particulate material. Investigations of the use of hard particles as additives were carried out by adding kaolinite of fine particle size as a dispersion material during the solidification process. Studies were made of short-time strength and of deformation characteristics. It was found that the short-time strength was not improved by the addition of kaolinite. However, the rate of deformation under a fixed stress was substantially reduced by these additions, as illustrated in Fig. 4. This finding is in general agreement with expectations from extensive metallurgical studies of dispersion hardening.

Deformable fibrous material. A deformable material, wood fiber, was tested extensively as a second-phase constituent in connection with the development of pykrete. Results of this study have been discussed by Perutz (*3*). They show that the addition of wood pulp to ice substantially increases short-time strength, increases resistance to deformation, and also increases resistance to impact and shock loading. With the addition of sawdust (about 15 percent by volume) the strength was increased by a factor of about 3, as shown in Table 1. Even more important, the reproducibility of strength values was much improved, so that the safety factor required for design purposes was much reduced.

Fiber of high strength and elasticity. For the temperature range from 0° to −40°C, an outstanding candidate as an alloying additive for ice is fibrous glass such as is used in reinforced plastics. Glass fibers have a high modulus of elasticity as compared to ice (10 million lb/in.^{2} as compared to about 0.2 million lb/in.^{2} for ice) and also high strength (about 250,000 lb/in.^{2} as compared to 150 lb/in.^{2} for ice). As a result of the high modulus of elasticity, an applied load is carried in large measure by the glass fibers, and the stress induced in the ice is limited to a minimum value. Experimental results more than exceeded expectations. The addition of Fiberglas (about 5 percent by volume) gave more than a tenfold increase in strength, as shown in Table 1. In addition, there was great improvement in deformation characteristics, as shown in Fig. 4.

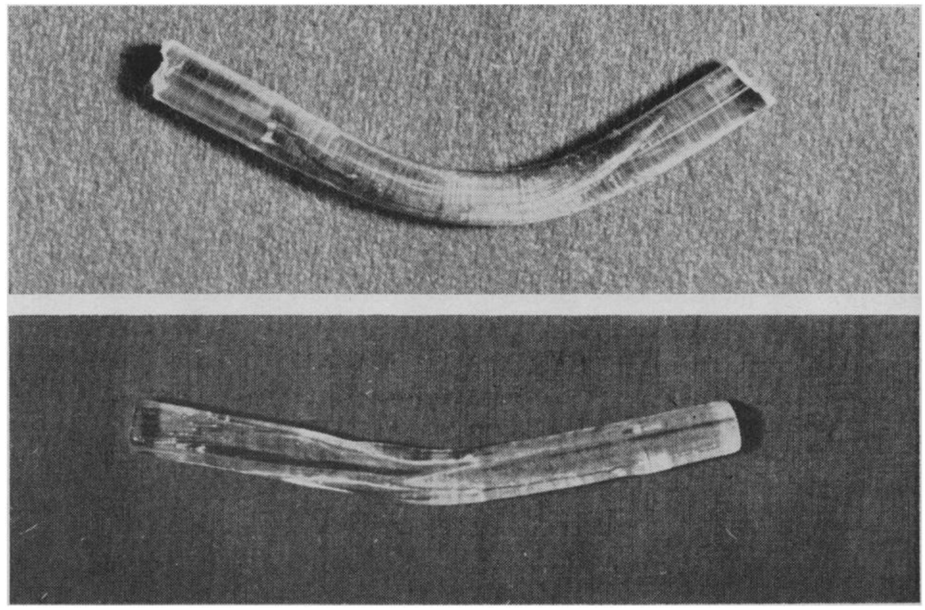

Fig. 3. Deformation (top) of a single crystal of sapphire at high temperature (in an oxyacetylene flame) and (bottom) of ice at a high relative temperature (close to the melting point).

Implications for Materials Science

The President's Science Advisory Committee, many other advisory committees to the Department of Defense, the National Academy of Sciences, and others have emphasized that we are up against a materials barrier in many areas of science and technology. New technical developments are often blocked by an inability to obtain materials with particular mechanical, electrical, optical, or thermal characteristics in a controlled and reproducible way. It is interesting to consider the implications for materials science of current studies of ice alloys.

The development of ice alloys has been based largely on the scientific understanding of fracture and deformation phenomena obtained by metallurgists and ceramists. Our current under-

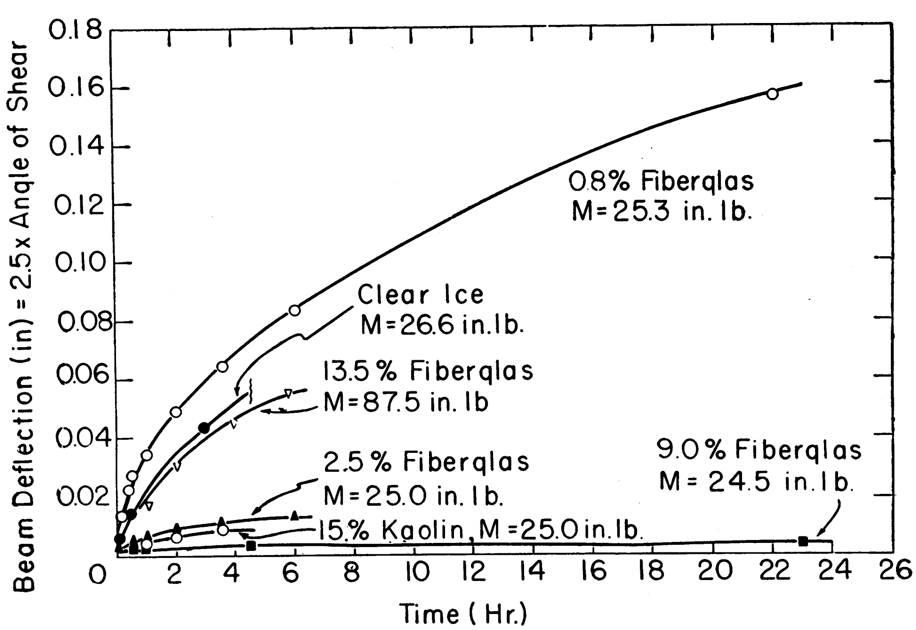

Fig. 4. Deformation of ice with various additions of kaolinite particles or glass fibers with bending moment *M*. The slope of the curve is the measure of apparent viscosity. [From W. D. Kingery (*2*)]

standing of fracture phenomena, recently reviewed (*6*), goes back to investigations by Griffith in 1920–21 (*7*). Our understanding of deformation characteristics is based on our knowledge of imperfections in crystals, called dislocations. Phenomena relating to dislocations have been intensively studied in recent years, but the essential idea was introduced by Orowan, Taylor, and others in the 1930's. On the basis of data on the mechanical behavior of pure ice and our current level of understanding of the mechanical properties of materials, it has been possible to predict the general behavior of potential ice-alloy systems and to concentrate research activity in areas suggested by our understanding of phenomena rather than by intuitive inventiveness.

Application of materials science and technology to a new system such as ice emphasizes the disparity between concepts limited by discipline (glaciology, metallurgy, ceramics, and so on) and those in which there are no artificial, disciplinary barriers. This is a case where exchange of information between different scientific disciplines has proved to be useful and effective (*9*).

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Is There a Sensory Threshold?

When the effects of the observer's response criterion are isolated, a sensory limitation is not evident.

John A. Swets

One hundred years ago, at the inception of an experimental psychology of the senses, G. T. Fechner focused attention on the concept of a sensory threshold, a limit on sensitivity. His *Elemente der Psychophysik* described three methods—the methods of adjustment, of limits, and of constants—for estimating the threshold value of a stimulus (*1*). The concept and the methods have been in active service since. Students of sensory processes have continued to measure the energy required for a stimulus to be just detectable, or the difference between two stimuli necessary for the two to be just noticeably different. Very recently there has arisen reasonable doubt that sensory thresholds exist.

The threshold thought to be characteristic of sensory systems has been regarded in the root sense of that word as a barrier that must be overcome. It is analogous to the threshold discovered by physiologists in single neurons. Just as a nervous impulse either occurs or does not occur, so it has been thought that when a weak stimulus is presented we either detect it or we do not, with no shades in between. The analogy with the neuron's all-or-none action, of course, was never meant to be complete; it was plain that at some point above the threshold sensations come in various sizes.

From the start the triggering mechanism of the sensory systems was regarded as inherently unstable. The first experiments disclosed that a given stimulus did not produce a consistent "yes" ("I detect it") response or a consistent "no" ("I do not detect it") response. Plots of the "psychometric function" —the proportion of "yes" responses as a function of the stimulus energy—were in the form of ogives, which suggested an underlying bell-shaped distribution of threshold levels. Abundant evidence for continuous physiological change in large numbers of receptive and nervous elements in the various sensory systems made this picture eminently reasonable. Thus, the threshold value of a stimulus had to be specified in statistical terms. Fechner's experimental methods were designed to obtain good estimates of the mean and the variance of the threshold distribution.

It was also assumed from the beginning that the observer's attitude affects the threshold estimate. The use of ascending and descending series of stimulus energies in the method of limits, to take one example, is intended to counterbalance the errors of "habituation" and "anticipation"—errors to which the observer is subject for extrasensory reasons. Typically, investigators have not been satisfied with experimental observers who were merely well motivated; they have felt the need for elite observers. They have attempted, by selection or training, to obtain observers who could maintain a reasonably constant criterion for a "yes" response.

The classical methods for measuring the threshold, however, do not provide a measure of the observer's response criterion that is independent of the threshold measure. As an example, we may note that a difference between two threshold estimates obtained with the method of limits can be attributed to a criterion change only if it is assumed that sensitivity has remained constant, or to a sensitivity change only if it is assumed that the criterion has remained constant. So, although the observer's response criterion affects the estimate of the threshold, the classical procedures do not permit calibration of the observer with respect to his response criterion.

Within the past ten years methods

The author is associate professor of psychology and a staff member of the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge. This article is adapted from an address delivered at a centennial symposium honoring Fechner, sponsored by the American Psychological Association and the Psychometric Society, held in Chicago in September 1960.