EDUCATION and the GENERATION of NEW IDEAS

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IT is an honor to be invited to participate in this panel discussion and to be entrusted with as provocative a topic as the relationship between education and the nascence of new ideas and points of view. Being very imperfectly educated myself and having had no new ideas that anyone would take seriously, I can at least bring an objective point of view to my discussion. The topic is too vast to undertake without some limitations, for education is, properly speaking, the entire phenomenon of intellectual growth, and I would like to conceive of it in this context as the later stages of the formal educational or schooling processes. New ideas have come to men at all times of life, though the more imaginative ones seem to have been brought by the angel of inspiration between the callowness of extreme youth and the onset of age-encrusted patterns of thought: tangential mental openings that these men and women were informed enough to discern and yet bold and uninhibited enough to pursue.

The broad concept of new ideas also needs a little refinement, for it becomes more meaningful if differentiated from mere innovation or deviation from the traditional norm. In the arts: graphic, plastic, lively and otherwise, or in the infinite variations and ramifications of human relationships, innovation or creativeness is an ephemeral kaleidoscopic phenomenon associated with the meeting of unfamiliar circumstances, or with divergencies stimulated by the manifold influences that play upon human behavior, or simply with spontaneous deviations from established social patterns. True, the plastic, graphic, dramatic, and musical arts evolve to some extent in response to the materials and devices that are available. But this has more to do with technology than art. Prehistoric pottery and stone, followed by metals in the order of their smelting temperatures, have succeeded one another as media of expression, but true novelty in artistic concept is difficult to discern even in the transition from the "round" of the Greeks to what might be called the "angular" of some moderns. It is apparent from the artifacts that have survived that we could teach the goldsmiths of Egypt three thousand years ago or the Greek craftsmen who flourished half way between then and now but little, and the painting of the Renaissance has yet to be surpassed.

Social or political concepts have been even more basically static in spite of the rise and fall of innumerable societies and states. Democracy in small communities flowered in the age of Pericles, but its critics existed as well, for Aristotle shortly thereafter defined its decadence as a perversion of good orderly polity. Autarchies, benevolent and otherwise, were old at the dawn of history; the Roman republic followed earlier patterns; and communism is familiar in primitive societies and the basis of the early Christian fellowship. Cruelty and kindness, fear and courage, knavery and honesty, duplicity and integrity have been the stuff of myth, legend, history, and fiction down to the present day.

But in the context of our century and particularly of this afternoon, new ideas can be endowed with a particular significance in the realm of science and technology, and it is with this area alone that I should like to be concerned. The crucial point is that here there is solid ground upon which to build; the phenomena are demonstrable; the definitions are procedural; and the data and their communication are least obfuscated by the ambiguity of language. Observations follow and supplement one another keyed

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neatly together into a coherent whole, and the artifacts and processes of technology evolve in sequence as our knowledge of and control over our environment advances.

It is here that the concept of progress acquires significance, and new ideas are recognized as the steps in fabrication, mastery, or understanding. It is true that theory, which is the simplified and consolidated description of phenomena in terms of verbalized concepts, tends to proceed somewhat more haltingly and disjunctively than does experiment, but men have always had more trouble with their heads than with their hands. But at least every sound advance in understanding encompasses as special instances the more partial expressions of earlier formulations, and the significance of a theory is measured not only by its adequacy in describing what is known but also by its fruitfulness in suggesting the way to crucial future observations. New ideas in the realm of technology may appear to some degree a misnomer, in that here novelty more frequently takes the form of new things or methods or procedures. However, within a sufficiently broad conception of science these represent innovations comparable to new ideas, new concepts, and new ways of relating ideas and concepts together in a simpler, more complete, and more perspicuous description of our environment.

THE series of events that we collectively designate as education for creativity in science is a sequence of seminal experiences between human beings, who participate together in the observation of phenomena and the analysis of these observations in the light of past and contemporary scientific records, which are concatenated by the thread of consciousness of the individual experiencing the education. The data we have on the nature of this remarkable intellectual process are very meagre and unsatisfactory, and though a considerable number of studies have been conducted that bear upon its success or failure, the findings of these studies lack much that could be desired in the way of scientific cogency. One difficulty is that the history of science and technology presents such a varied scene from ancient inspired speculators, through a long exiguous period marked by a few gifted observers and synthesizers in successive generations who were related by the fortunate chances of preservation and availability of earlier records, to the exponential crescendo of growth and activity of our present day when we are in danger of being choked by a polyglot flow of output which it is beyond an individual's ability to survey and comprehend.

As an instance, one may consider the story of the category of forces we designate as gravitational. It is a long and fascinating one beginning with a burst of quite precise observations two or three millenia ago in Mesopotamia and the Nile Valley. This was followed by an arid period of error and ignorance until the sixteenth century when pioneers appeared in the persons of Copernicus and the observer, Tycho Brahe, whose discoveries were synthesized and extended in the seventeenth century by Kepler and Galileo, leading to the major triumph of Newton in the eighteenth century. The nineteenth saw the rapprochement with mathematics through Gauss, Lagrange, and Laplace and with physics through Fraunhofer, Kirchhoff, von Helmholtz, and Young, which led essentially to the coalescence of mathematics, astronomy, and physics which in turn laid the foundation for the enormous strides of scientific knowledge into the regions of cosmology and nuclear physics by men known to our own generation. This is an inspiring vista of skilled and diligent men of widely diverse talents, each motivated by an intense intellectual curiosity, handing on a torch of accumulated knowledge until it resulted in the brilliant conflagration we know today.

A second instance may be chosen from technology, which is one of the confluent streams nourishing our present scientific strength. The comparison of the history of the evolution of the heat engine with that of our knowledge of gravitational phenomena brings out certain similarities as well as instructive differences. The devices which utilize temperature differences to perform work had their small beginning two millenia ago in Alexandria when Hero, a mechanic and follower of Archimedes and Ctesibius, devised and constructed an elementary type of reaction turbine, the utility of which was primarily limited by the primitive state of the ancillary technology, though it was used to raise water and open temple doors. Again a long dormant period intervened until the sixteenth century when della Porta explained how steam pressure could be used to raise water and how its condensation could be caused to suck a fluid up within an enclosure. The limitations that were observed to apply to the latter process and the desire to employ this process in pumps led to investigations by Galileo and his pupil Torricelli which elucidated the phenomena related to atmospheric pressure. Urgent need for the pumping of water and the draining of mines lèd to Lavery's simple engine, severely limited by the strength of available materials at the end of the seventeenth century. This was followed by Newcomen's contribution of combining a cylinder and piston in a reciprocating machine at the beginning of the eighteenth century and Watt's great step forward in the incorporation of an external condenser and the achievement of some efficiency in the second half of that century. The steam turbine was first thought of in Watt's time but it was not until there was the urgent need for driving dynamos that Parsons evolved the first satisfactory embodiment of this principle and received his patents in 1884. Somewhat before this event Lenoir's gas engine was invented, and the need for a light engine to power small plants and vehicles led Gottlieb Daimler of Würtemberg to the devising of the carburetor and the petroleum engine in almost the same year that Parsons patented the steam turbine. The nineteenth century saw the establishment of the fructifying connection of this technology with science through the work of Joule, von Helmholtz, Carnot, Clausius, and Kelvin, and the foundation was laid for the powering of the present century.

A comparison of these two brief historical synopses suggests certain interesting observations that bear upon our theme of education for inventiveness in science. Early flashes of genius such as those of Democritus and Hero can and do go out, leaving no spark to kindle future men if not supported by the discipline and structure of science, the presence of like-minded colleagues, and a responsive technology. Education is contributory to progress if it fits men for opportunities that exist. The long period that was relatively unproductive scientifically before the Renaissance was one of such turmoil and social dislocation as to preclude any orderly scientific effort, and education in the ages of faith and dogma was such as to inhibit new ideas and scientific speculation or accomplishment. The reformation and enlightenment brought relative freedom of thought, speech, publication, and assembly. It lifted the burden of consuming preoccupation with the misery of this life and the glory of that to come, and ushered in an atmosphere in which early science flourished to the extent permitted by the mathematical tools of expression and the technological tools of manipulation.

Finally, it would appear that the rates of growth in science and technology are roughly parallel, each being dependent upon the other. They are, of course, dependent as well upon the antecedent body of relevant knowledge and accomplishment, and they are greatly enhanced by the establishment of appropriate connections between previously disparate fields of interest. The men whose names are associated with the growth of science are of all sorts of characters and temperaments, bents and predilections. They share, however, the characteristics of energy and diligence, clarity of thought and skill in their professions, and the ultimate of respect for precise and honest observation and experiment. They are all motivated doubtless by some satisfaction in logical syntheses or in the creation of things or methods, but while the scientist is primarily spurred by curiosity, the technician is more often impelled by the practical need for a device or system.

OUR educational institutions are primarily the men and women who are assembled in them, though their successful performance is conditioned in part by their structuring and conduct and by the support and encouragement they receive from society. If new science and technology are to be generated in them, they must be populated by the kind of men who are of an innovating temper, and who possess some of the characteristics we discerned in the men who systematized our knowledge of the universe and who harnessed heat energy for our use. These are not quite so readily descried in our contemporaries as in our predecessors: for instance, Willard Gibbs, the father of physical chemistry, Ross Harrison of tissue culture fame, and others of like stature who come to mind were not awarded Nobel Prizes in their days. On the other hand, there is much less diversity of view in the assessment of scientific merit than of that in any other field, and by and large the scientific faculties of our universities do number amongst them a large fraction of those persons who, by a quite universal consensus, are imaginative and productive and of a caliber to elicit like qualities in their students. While there is room for almost every scientific temperament on a faculty, the recluse, the misanthrope, or the man of a single narrow interest are least at home, for education is fundamentally a matter of intercommunication and mutual inspiration and stimulus in which breadth of interest and a sincere and vital concern for others are large components in successful participation and in the rewards it brings. The presence of these people upon a campus is the primary requisite for the generation of new ideas in a scientific discipline, and as one looks back at the great schools of Thomson, Bohr, Rutherford, and Lawrence and around one at the more numerous contemporary examples, one sees the process spread out before one's eyes.

The selection of promising students for the junior component in these institutions is a more difficult and chancy business. They have not had the opportunity for displaying Carlyle's criterion: "the transcendent capacity for taking trouble". Some of the art of a great teacher is in the selection of his students, and being transient, the errors—like those of a physician—tend to pass from the scene and not mar the record. But the problem of ensuring that the ablest and most talented young men and women have the opportunity of an appropriate educational experience is a very real and urgent one for which we have no very satisfactory solution today. What evidence there is indicates that in America we do rather less well than in other countries. As an instance, George Gray has computed the number of Nobel Prizes per capita. In this listing Denmark leads, followed by Switzerland, Sweden, Holland, Austria, Germany, Great Britain, and the United States in that order; and the per capita incidence of these prizes is five times as great in Denmark as with us. Inadequacies in elementary and secondary education are, of course, an important component in this situation. If we are right in thinking that the freshness—and even brashness—of youth is an important component in the flowering of genius, it is important that the basic rote learning of logical thought in mathematical language and communication in the vernacular be well and soundly mastered very early in one's career and should not require shoring and patching up on through colleges and universities. This thesis is supported by Gray's statistics and the general concession that European schooling is more rigorous in these essentials. The heterogeneity of our population and the broad diffusion of educational objectives in our high schools to meet the diverse demands upon them play some part as well. The cost of higher education in the United States is not without its influence. But probably the most important factors are the prevailing general ignorance of the opportunities and rewards of a scientific career and the relative values accorded by Americans in general to careers of various sorts, both of which tend to reduce the number of promising young men and women who elect to become scientists.

But even among those students applying for admission we can take no greater satisfaction in our discrimination. Verbal and mathematical aptitude tests and others of this nature not surprisingly correlate quite well with performance during the first few years in college where the requirements for success are inherently correlative to the nature of these tests. Validation of such tests and the other conditions for admission that we impose against the criteria of later performance as a scientist are very imperfect and inconclusive.

A study by Lewis Terman of scientists and nonscientists in a group of 800 gifted men over a period of 30 years, based on childhood intelligence tests, indicates some positive correlation, but possibly its most interesting conclusion is that childhood interests, preoccupations, and behavior patterns would appear to carry far on in life and provide a better basis for career counseling than any test performance.

GIVEN that the most inspiring and most promising participants in the educational process are assembled on the campus, wise university policy and good departmental tradition can contribute to the successful pursuance of the enterprise. Also the nature and extent of the support that the institution can attract from the broadest array of sources is important in determining its rate of productivity.

There are a few matters concerned with beginning courses that bear reiteration. One is that though this is the place where a sound basic foundation of scientific principle and method is to be instilled, it is also the time when individual enterprise and the responsibility for his own education on the part of each student must be awakened. Academic tradition must not be allowed to countenance the dull and the routine, and the precision of the mathematical language must be learned without overshadowing the substantive significance of the matter being discoursed upon. Intimate contact with the phenomena themselves must be included in demonstrations and laboratories or the spirit of the entire venture is lost.

Looking at the larger program, including advanced, graduate, and postgraduate participants, the concept of the academic community should be emphasized in which instruction and research are two essential and interrelated aspects of the same educational or learning process; the former applying more particularly to the junior participants and the latter to the senior ones. In its best exemplifications the sub-communities are not sharply limited to a narrow discipline but include fringes of men from neighboring departments impinging both on the theoretical and applicational extensions of a department's interests. In 1960 The Panel on Basic Research and Graduate Education of the President's Science Advisory Committee had a number of wise words to say on this matter: "It is a fundamental contention of this report that the process of graduate education and the process of basic research *belong together* at every possible level. We believe that the two kinds of activity reinforce each other in a great variety of ways, and that each is weakened when carried on without the other. We think also that this proposition has substantial implications for the policy of both the federal government and the universities." And: "But once the emphasis is placed squarely on the student's need for the best possible experience in graduate school, assisting in the research of others and sharing in the work of teaching can both be intensely valuable parts of a good education, and in our eagerness to prevent abuse we should not make rules which cut students off from such opportunities. In particular, fellowship programs should not exclude the student from part-time assignments in research or teaching, and unless the fellowship is so large as to make any additional stipend unreasonable, there should be no obstacles to an appropriate payment for such services."

Finally, in the matter of the resources which in the American tradition are drawn upon to support our fundamentally uneconomic institutions of higher education, it goes without saying that any which carry with them restrictions of dogma or propaganda or that require specific performance inimical to educational integrity must be eschewed. Otherwise, breadth of base is a bulwark of self-determination and to be welcomed. Though endowment is falling in its relative contribution as are state contributions nationwide, the roles of individuals, corporations and foundations are rising, and the promise of increasing federal participation is encouraging. The case is put in terms of investment in the report of the Panel previously referred to: "But scientific and technological investments are still more powerful tools, since they invest in the discovery of what we do not yet understand. We are only just at the beginning of the use of scientific investment in this large sense, and the returns it can bring in are literally incalculable. Simply in terms of economic self-interest our proper course is to increase our investment in science just as fast as we can, to a limit not yet in sight."

The Panel properly says that universities attempt to do too much with the means available: "Yet the main trouble in the universities is not a failure of understanding or communications; it is a lack of means. Typically the American university is trying to do too much with too little. Its salaries are low; its teaching assignments are high; its scientific buildings and equipment are cramped or out of date, or both. Modern science does not flourish in such circumstances. Dedication and talent are still the first requirements for scientific achievement, but in most branches of science today there is no escape from the need for expensive facilities and substantial numbers of colleagues. No university in this country today is doing what it should in science; none could be doing even as much as it is without the federal support which has developed in the last 15 years. Thus, partnership between the universities and the national government is the indispensable basis for first-rate university work in science." But the course of good education in the interests of scientific progress is one in which it is easier to forgive the overambitious than the cautious laggard.

A fitting conclusion to any examination of the emergence of new ideas in science is furnished by Sir Francis Bacon, who in the sixteenth century adumbrated the basic philosophy of modern science and who was himself an energetic man of affairs, an eschewer of the vague and philosophical, an insister on the experimental method and demonstrable evidence, and a man alight with intellectual curiosity who in the second book of his "Advancement of Learning" wrote as follows: "Invention is of two kinds, much differing; the one, of arts and sciences; and the other of speech and arguments. The former of these I do report deficient; which seemeth to me to be such a deficience as if in the making of an inventory touching the estate of a defunct it should be set down *that there is no ready money*. For as money will fetch all other commodities, so this knowledge is that which should purchase all the rest. And like as the West Indies had never been discovered if the use of the mariner's needle had not been first discovered, though the one be a vast region and the other a small motion; so it cannot be found strange if sciences be no further discovered, if the art itself of invention and discovery hath been passed over."