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INCREASING THE PRODUCTIVITY OF RESEARCH[1]

By Dr. PAUL E. KLOPSTEG

DIRECTOR OF RESEARCH, NORTHWESTERN TECHNOLOGICAL INSTITUTE, EVANSTON, ILLINOIS

VERY few scientists have had opportunity during the past five years of engaging in research of their own interest and choosing. The demands of war have placed urgent emphasis on the need for developing practical embodiments of scientific principles with the purpose of providing our armed forces with all manner of new devices more potent in warfare than those of the enemy. To this end, the great majority of our scientists and engineers in university and industry and in the laboratories of government departments have been united in a common effort, on a scale without precedent, bringing to bear upon the problems presented a vast resource of ingenuity, drawing upon an equally vast store of scientific knowledge and practical experience. Their accomplishment will speak for itself when security regulations will no longer prevent disclosure. It is matched only by the miraculous accomplishment of American industry in producing the equipment and supplies by which our armies and navies and those of our allies have so competently brought their tasks of unprecedented magnitude so near successful conclusion.

The productivity of our scientists and engineers in the war effort has been possible because of the large numbers engaged in work of common character; the unlimited funds and facilities available for the work; and the strong stimulus of doing something potentially valuable in helping to win the war. To those who have had opportunity of seeing many aspects of war research, it is apparent that most of

[1] Delivered before the Northwestern University Chapter, Society of Sigma Xi, Evanston, Illinois, May 18, 1945.

the activity has been developmental. Its contribution to fundamental knowledge has been small. Rather, in a manner of speaking, it has been eating into our reserves of fundamental knowledge and has been making applications of that knowledge to destructive purposes. Although we admit this with extreme regret—regret that the greatest effort in scientific activity that the world has ever known has had to do with destruction and devastation—there has been no alternative. But the time has come when we may again think and plan in terms of peaceful pursuits, with the hope and expectation that the results of our future efforts may be beneficial and restorative and contribute to human welfare and contentment.

The word research has been defined in many different ways, depending, perhaps, on the interests and associations of the person writing the definition. The kind of research that has as its objective new developments for industry is whimsically defined by C. F. Kettering as "the process of finding out what we're going to do after we can't keep on doing what we're doing now." That definition, though pointed and epigrammatic, does not quite meet the needs of this discussion. In order that we may have a common understanding of the meaning of the term, I should like for our purposes to propose the following:

> Research is original and creative intellectual activity carried on in the laboratory, the library or in the field, which endeavors to discover new facts and to appraise and interpret them properly in the light of previous knowledge. With constantly increasing understanding, it revises previously accepted conclusions, theories and laws, and makes new applications of its findings. Whether it seeks to extend knowledge for its own sake or to achieve results with specific economic or social value, its *raison d'être* is its contribution to human welfare.

Having established a definition of which most of you would approve, let us get on with our subject, "Increasing the Productivity of Research." The implication of this title is that there is need for enhancing and augmenting the results of effort devoted to research. Although we may wishfully hold the opinion that support for research should be unlimited, or that the need for such support should not be questioned, it must not be forgotten that in the last analysis funds for conducting research are provided by the public, whether the channels through which they flow are those of government, commerce, industry or, indeed, whether they are gifts from private sources. That research needs doing need not be argued. Its results, so far as modern living is concerned, envelop us, and speak for themselves. But are we in position to argue that the effect upon the world would be disastrous unless some annual quota of research output were reached? Obviously not. What we can and do say is that the greater and better the output, the more will the world benefit by the results, and the more rapid will be our climb towards better living—better in the broadest meaning of that word. Nor can there be any doubt that we must continue to add to our reserves of fundamental knowledge, and that need will arise in many directions to apply existing knowledge as well as newly acquired knowledge to immediate problems. As the problems of war are left behind, and postwar activities are undertaken, the first great change that the many thousands who were engaged on government contracts will notice is the necessity for readjustment to a greatly diminished scale of support. Another change is that the pressure to get the job done will have been much reduced. We shall again be pursuing our work in more leisurely fashion and shall have time for the meditative and reflective aspects of investigations without the inevitable interruptions that the abnormal conditions brought upon us. Notwithstanding the reduced pressure and the consequent improvement in environment for scholarly endeavors, we are in agreement, I am sure, that research should be conducted with the purpose of achieving the best results both in quality and quantity in relation to the available time and the effort and money applied to it.

As we view the postwar picture we shall discern quickly that the number of competent research workers will have become greatly diminished during the war years, by death and retirements at one end of the age scale, and by almost complete cessation of replacement at the other. This question has been discussed in a number of recent articles. It is a subject of many implications, which must be of much concern to scientists. We lack time to treat it extensively. My only purpose in bringing it into this discussion is to introduce the fact that in our postwar research there will be a period of perhaps ten years in which we shall have far fewer research workers than our institutional and industrial laboratories will need. This is one factor that bears on the problem of increasing the productivity of the individual doing research.

As we consider quantity and quality of research, we feel keenly the need for some way of measuring the output. The only unit we seem to have, and which is patently not a measure of output, is the number of dollars that support it. Numbers of pages of published results are sometimes used as a gage of scholarship upon which advancement in professional status depends. To my knowledge, no one has ever found a formula for converting this number of pages to a figure of merit of the work set forth in the publications. The evaluation of results of research, from the standpoint of human welfare and benefit, has, in short, not been reduced to measurement. We can therefore speak only in relative terms and say that we hope for more and better research, or that our output of valuable results per dollar ought to increase. That this hope is justified rests on the conviction that the point of diminishing return per dollar spent has not been reached, that we are, in fact, far from it, and that it is not likely to be reached within predictable time. Thus it appears self-evident that all possible means to increase the effectiveness of our research should be employed. I should like to explore with you some means for accomplishing this purpose.

It is generally recognized that progress in science is intimately associated with and dependent upon availability of instrumental aids for observation, measurement and control. To this thesis, Zeleny[2] devoted his retiring address as vice-president of the American Association for the Advancement of Science and chairman of Section B in 1916. In the industrial field, the word "instrumentation" has come to mean the control, by means of instruments and devices based on measuring techniques, of industrial processes. I should like to introduce a new and broader term—"instrumentology"—a contraction of "instrumental technology"—to denote the science and art of applying instruments, and methods used in association with instruments, to extending our powers of observation, to the making of accurate measurements, to the precise control of ambient conditions and to the analysis, reduction or other processing of data.

If you are an Einstein or if, perchance, your field is theoretical physics or pure mathematics, the only equipment you will need is pencil and paper. The great majority of scientists are, obviously, not Einsteins; nor are they theoretical physicists or mathematicians. Even in these categories, the validity of paper-and-pencil research, except, perhaps, in the field of pure mathematics, can not be established without the use of instrumental methods.

Three decades ago it was still possible for the individual research worker, in most fields, to familiarize himself with instrumental methods that might be of use to him in his own researches and, with some months of application, to become reasonably expert in applying the chosen instruments to his problems. During the past three decades, however, the field of instrumentology has become so complex and has advanced with such speed that no individual scientist could hope to keep pace with even a small section of the advancing technology. It hardly needs pointing out that instrumentology makes applications primarily of physical principles. Yet there is not a physicist, I dare say, who is intimately familiar with the principles and the details of all the instruments that have been described or that are available for all the kinds of measurement, observation and control that might find useful application in the research laboratory. Since instruments make applications of fundamental physical principles, the physicist may be in somewhat better position to comprehend broadly what is possible with instruments, what is available for use, and, in general, how they may be applied to specific problems.

If the physicist, in whose domain the principles of instruments lie, can not hope to keep currently abreast of instrumental developments, what shall we say about the biologist or the psychologist or the engineer or the research worker in medicine whose researches distinctly call for an application of instrumental methods? Unless the biologist happens to be a biophysicist, the psychologist a psychophysicist, the geologist a geophysicist, or the chemist a chemical physicist or physical chemist, it is unlikely that in the course of his training or experience he has acquired more than a nodding acquaintance with instrumentology. If in his—let us say, biological—research problem the application of instruments is clearly indicated, what course should he pursue?

He thinks his problem through. In this reviewing process it occurs to him that his friend Jones in the department of physics is more or less expert in this particular field which may call for the application of electronics to the precise control of some particular environmental condition. He goes to see Jones and talks the problem over with him, hoping, but not expecting, that more aid than a few helpful comments will be forthcoming. His negative expectation is realized. Jones, the physicist, has his own problems. He is courteous and friendly and helpful enough, to a point, but beyond that, Smith, the biologist, has to shift for himself. Fired with enthusiasm and zeal to get into his problem and make headway with it, he studies the references that Jones has given him, and after some weeks of intensive application he feels reasonably qualified to go ahead, employing an instrumental procedure that he hopes will do the job. Unfortunately, the particular instrument that he has decided upon using is not regularly available from the dealer in scientific instruments. If it were, the chances are that Smith's research would have been done long ago. He is working in a new field in which biology and physics overlap and, consequently, no specific instrument has been devised for the application he has in mind. So he sets about designing the instrument, with occasional help from Jones in selecting the proper components for the electric circuits and, perhaps, an optical system, and after some weeks more the device is put together and, with sufficient

[2] SCIENCE, 43: 185, 1916.

"debugging and doctoring," it is made to operate, after a fashion. Smith has spent several months doing things that he should not have to do, things with which he is not particularly familiar or particularly expert. He finally gets his research under way. Although the instrument falls a bit short of his expectations, he eventually gets his results and publishes his paper. In all probability the research turned out less well than it might have, had he been in position to devote his entire time to intensive study of the problem in his own field of specialization.

Now let us take another view of the same problem. The university with which Smith is connected is a fairly large, well-established institution. The administration has accepted the truism that a university has the traditional obligation to the public to foster and facilitate research among the scholars who comprise its faculty. It has established adequate libraries to enable its scholars in the non-laboratory fields to do distinguished work. It has also recognized that for equally distinguished work in the many fields that depend upon instrumentology there must be available the facilities for providing and applying such methods. There has consequently been established a group of research service centers, including a laboratory headed by Brown, a specialist in electronics, for whom it is as simple to design a circuit for a specific purpose as it is for Smith the biologist to plan a problem in which the use of paramecium or drosophila is indicated. Smith is aware that one of Brown's assigned functions is to consult with men like Smith, to assist them in devising the electronic aids for carrying on their researches. Brown has in his laboratory several technicians trained in putting electronic circuits together and making them function properly. After discussion with Smith, he directs one of the technicians to build a device which he then turns over to Smith; more than that, he assigns the technician to assist Smith in putting it in operation and use. Smith has been saved a number of months of study and effort in a field in which he is not a specialist and in which he is not particularly interested, and has saved the time for the effective application of his greater knowledge of his own field.

The word picture I have just given will, I think, offer an insight into a proposal which should be considered in every university that extensively supports scientific research. It will also suggest a plan which I am confident will vitalize scientific research in a university and materially increase the valuable output per dollar of the funds that support its research.

A group of research service laboratories of the kind that assisted Smith in his problem is, in my opinion, potentially the most effective agency that can be devised for assisting research in all departments of science. *They are the laboratories of instrumentology, whose work constitutes a technology consisting of the application of science to science itself.* Under this plan a university would have available a group of specialists able and ready to consult with any research worker in the university, whether in pure or applied science, engineering or medicine. These specialists would assist the research worker not only with advice but by the loan of qualified personnel, either to familiarize the research worker himself with a method or procedure, thereby enabling him to carry on without further assistance; or, in the case of the highly specialized, complicated instrument, to operate the instrument.

It would be wearisome for you to have to listen to a portrayal of details of all the laboratories that might comprise such a group. A quick review of some possibilities, with brief comments, may prove interesting. I would not confine the subject-matter of the laboratories to physics because there are techniques and procedures in chemistry and mathematics, for example, that are as much a part of instrumentology as are the techniques of physics. In the Office of Scientific Research and Development it was found not only valuable but essential to establish a group of mathematicians, known as the Applied Mathematics Panel, to assist the research workers in the various fields of activities covered by the National Defense Research Committee. It is equally important in peacetime research to have mathematical aid for research in the sciences, in economics and in other fields.

I would therefore place on my list of research service centers a laboratory of applied mathematics, equipped with all the latest calculating machines and devices for which research in the university might find need. Working closely with it, and possibly cooperating in the design and development of new mechanical, optical or electronic means for performing complicated mathematical operations, might be a laboratory for specialization in methods of control, including such war-tested indispensable devices as servo-mechanisms. There would be a laboratory specializing in microchemical techniques; another one employing the instrumental facilities that have proved so effective in physical chemistry and electrochemistry. To keep abreast of the important new developments of materials there would be a laboratory of metallurgy and metallography, another dealing with the technology of plastics and wood, another with fibers and textiles, still another specializing in high-polymer physics and chemistry. In these four laboratories would be found men with qualifications to handle all problems having to do with the properties of materials; they would have particular significance in many aspects of engineering.

Still another group would deal with meteorology and geophysics, the latter presumably having much potential value for a department of geology which realizes that great progress is possible in the application of physical methods to its problems. There would be a laboratory specializing in problems of heat and temperature and the measurement and control of these quantities, and one dealing with problems of vibration and acoustics. There would be a laboratory specializing in the applications of such techniques as measurement of relative masses of atoms and molecules with a mass spectrograph. Another would deal with spectrography and spectrophotometry, extending through the visible and the adjacent invisible regions of radiant energy. There would be laboratories specializing in applied optics, including polarimetry, photoelasticity and applications of photography as well as other uses of optics in research. Applications of electrical measurement and control, of electronics and gaseous conduction, of x-rays and radioactivity, would constitute a group of technologies employing the developments particularly of the past several decades. Others would be established as the need arose and new methods and procedures became available.

One of the laboratories mentioned would be equipped with an electron microscope. This instrument has found diversified applications; but since its cost, and at present its size, are such that it would hardly be feasible to provide an electron microscope for every department of a university that might use it, an instrument centrally available would serve an exceedingly useful purpose for many departments and many kinds of research. In charge of the microscope would be a technician who has been thoroughly trained in its use and who could therefore apply it to any particular problem to best advantage. The same thing may be said about a mass spectrograph, perhaps a betatron, and other instruments similar in kind.

Associated with such laboratories there would be all the shop facilities required to render their work effective. The shop would be equipped with precision tools for the working of metals, wood, plastics, glass and other materials useful in research. The shop, indispensable and invaluable to the laboratories, would provide personnel specially trained in general laboratory techniques, such as setting up optical systems, vacuum systems and systems for maintaining pressure, rates of flow and other quantities at desired levels. Its superintendent or an assistant would aid in developing the mechanical designs of special apparatus with reference to simplicity and ease of construction.

You will before now have detected the principal difficulties in making such a plan work effectively. One of these is the problem of finding and assembling a well-qualified staff endowed with sufficiently broad vision and understanding to appreciate the important part it can play in the advancement of science. A university administration, as well as a directing head of such a group of laboratories, must realize that these are as essential to research in science as is the research library to the non-laboratory fields of scholarship. The scientist responsible for any particular laboratory must have understanding of and be sympathetic with the problems of the scientists in fields other than his own. His value is enhanced if he familiarizes himself with the general aspects of the several fields of science that his laboratory has been established to serve.

Another, and the only other major problem that may impose difficulty in carrying such a plan to successful realization, is that of kudos for the scientists who comprise the staff of the laboratories. The person responsible for any one of the fields will of necessity devote some of his time to the problems of his colleagues in the university. He may or may not develop material suitable for publication, to show for the time thus spent. But, on the credit side of his picture, is the fact that his own research will consist in extending his technology to the problems that will either be presented to him or that he himself may find and suggest to the specialists in the field in which that problem falls. The extension of his technology, together with the development of new and improved instruments within his field, will be his research. More than that, however, may be confidently expected. His own horizon will expand, and he will discover problems that would not otherwise occur to him.

As such laboratories come into existence and begin their activity in the service of science in a university, more and more researches will develop in those areas in which contiguous sciences overlap. Here the specialist in instrumentology and the scientist with whom he joins his interests will become co-workers and joint authors of papers describing the results of their cooperative research. The problems brought to the instrument specialist by scientists from fields outside his own will stimulate his interest and imagination so that he becomes more productive in his own field. There lies ahead also the strong probability that the scientist who has been assisted by one of the laboratories of instrumentology will develop an output of research with higher quality and greater frequency than would be remotely possible for him with equal effort spread over activities with which he should not have to concern himself.

The proposed plan is capable of stimulating and developing the research potential in another way. The training of students in the theoretical fundamentals, in the scientific method and in the practical applications of the scientific method employing the powerful tools of instrumentology—such training can make great contributions to research in a long-range program. The conduct of such training might logically become the responsibility of a department of applied science, which would also be the logical responsible agency to conduct the activities of the laboratories of instrumentology. Basic courses in mathematics, physics and chemistry, in such concentration as might be supported in the curriculum, would constitute its foundation. All these courses would be planned in cooperation with and offered by the departments representing these several fields of knowledge. In parallel with the fundamental studies there would be general and specific courses in instrumentology, with supporting electives. These would be enriched and broadened and liberalized by courses chosen for that purpose, and it need hardly be added that sufficient training in English would be included to assure ability to express ideas clearly. This plan would provide training of a kind not now available. It would provide foundations of education for biophysicists, and for physicists with intensive training in other directions, such as petroleum technology, metallurgy, acoustics and optics, to cite only a few examples. A student who had completed work to the bachelor's or master's level in such a curriculum would be well prepared for service in many kinds of industry. He would be equally well prepared for graduate work looking towards advanced degrees.

This discussion of the training of students tempts me to digress long enough to put before you a brief outline of what seem to me to be the objectives of education—an outline that I would use as a general guide in conducting the kind of course I have in mind. During an industrial interlude of more than twenty years my interest in education never faltered, resting as it does on the firm conviction that the hope of a better future lies in better education and better research. The outline, crystallized out of personal experiences, out of a great deal of time available for thinking while traveling endless hours during the past five years, and out of many discussions with educators, directors of research, personnel directors and government scientists, is an attempt to set down these objectives in a single typewritten page. Please observe that no distinction is made between "liberal" and "technical" education. For this failure to distinguish, if failure it be, I offer no apology; I have been unable to persuade myself that education should have restrictive labels.

The objectives of education are to develop knowledge, the arts, manners, and wisdom.

Knowledge is a comprehension of information, facts and theories, and an understanding of interrelationships among them. It is acquired most effectively by thoughtful reading, discussion and observation, and by the development of good habits of study through the exercise of self-discipline. Methods of acquiring knowledge are more important to the student than knowledge itself.

The *Arts* are the "know how" of doing. They can not be learned by reading. They are acquired under competent guidance and direction, with ample opportunity for the student to train himself and to develop his creative talents, curiosity, imagination and ability to think. Much of the content of education is knowing how to do things; it is ability to apply mental and manual dexterity, and to plan and direct the attack upon a problem. Applied mathematics and applied science are examples of the advanced arts; so is applied English—the ability to write a report with clarity and brevity. Many problems of the future will demand both knowledge and the arts at high levels of attainment.

Manners, in its simplest aspect, is social behavior—the attitude of the individual towards others. The development of good manners depends in larger degree upon example and advice to the student by members of the faculty who themselves have attained a high level of social behavior than it does upon formal courses. Cultural subjects, such as history, philosophy, economics and sociology, contribute to such development, and assist in providing unification and integration among the several factors that comprise education. The student should acquire a consciousness of his obligations to society, and of the indispensability of personal integrity and responsibility in his dealings with others. Home and community influences are perhaps more potent in the development of good manners than anything that school or college can do.

Wisdom is the attribute exemplified by sound judgment and common sense. It governs the way in which knowledge, the arts and manners are applied in any particular situation. An indication of wisdom is the ability to appraise a set of circumstances, to foresee their implications, and to initiate action that will assure attainment of desired ends. Since wisdom depends for the most part on an inherent aptitude, or "native intelligence," formal education can not beget wisdom, nor is its possession a monopoly of those who have had formal education; but the educational process can be significant in its development. Experience with things and people enriches wisdom.

If the educating process achieves the objectives of imparting knowledge, and developing the arts, manners and wisdom in a student, it may be accounted successful.

To resume the main theme, it is my strong conviction that the establishment of a department of applied science in a university, designed to train students in research, and to serve the various departments of science, medicine and engineering, will find even greater opportunity for public service in the fact that it will render the output of the various departments more significant not only as regards fundamental knowledge but also in the application of such knowledge to specific problems. The specific problems for the most part will arise in industry and come into the university as research projects in which the university and industry participate, on a cooperative basis. Research to increase fundamental knowledge and research to apply that knowledge will thereby be enriched, the immediate beneficiaries being the university and industry, and through them, the public. Thus, the establishment of a department of applied science in a university, along the indicated lines, would, in relation to effort and expenditure, do more to vitalize and stimulate research, both fundamental and applied, than any other comparable measure; and its output of well-trained graduates and postgraduates would make a further major contribution towards increasing our total output of results at high levels of quality.

I am not unaware that the picture I have tried to present of a department of applied science, with its laboratories of instrumentology, may remind some of you of certain passages in Revelations, describing visions of a great city of white marble, in which the streets are paved with gold. Should that be your impression, my comment is that without vision we shall make no progress; and if, perchance, we are granted vision, shall we not think in terms sufficiently inspiring to set a goal for which it will be worth our while to strive?

OBITUARY

WILLIAM HENRY HOWELL
1860–1945

THE death of Dr. William H. Howell on February 6, 1945, marks the passing of the first group of professional physiologists in the United States, and of the galaxy of talent entrusted with the organization of the departments of the Medical School of the Johns Hopkins University prior to the opening of its doors to students of medicine in 1893. With his death America has lost one of the leading figures in physiological science.

William Henry Howell, born in Baltimore on February 20, 1860, was the son of George Henry and Virginia Magruder Howell. William Henry was educated in the public schools of Baltimore. In his senior year at City College, as the Baltimore high school is designated, he left school to become assistant to the professor of physics and chemistry. In the fall of 1878 he entered the Johns Hopkins University as an undergraduate student in the chemical-biological course to prepare himself for the study of medicine. Upon his graduation in 1881 he was awarded a graduate scholarship and because of this he matriculated in the graduate school as a candidate for the degree of doctor of philosophy, instead of following his original intention to study medicine. However, while pursuing his graduate studies he took extra-mural courses in anatomy and attended clinics at the Medical School of the University of Maryland. He was awarded the Ph.D. degree in 1884.

In 1885 he was made chief assistant in biology under his teacher, Newell Martin. Subsequently he was promoted to the grade of associate and, finally, associate professor of biology, in which capacity he gave the lectures in animal physiology in the undergraduate courses. In 1889 he was appointed lecturer and in 1890 professor of physiology in the University of Michigan. In 1892 he accepted appointment as associate professor under Dr. H. P. Bowditch at the Harvard Medical School and in 1893 he became the first professor of physiology of the Medical School of the Johns Hopkins University.

For twelve years, from 1899 until 1911, he served as dean of the Medical School, succeeding Dr. Welch, the first dean. When the School of Hygiene and Public Health of the Johns Hopkins University was founded in 1918 he severed his connection with the Medical School to accept appointment as assistant director and professor of physiology in the School of Hygiene. Eight years later he succeeded Dr. Welch as director of that school. He retired in 1931, but was provided with a laboratory by the university and, with funds supplied first by a research foundation, and subsequently from the fluid research fund of the Medical School, he continued with research almost to the day of his death, though he knew he had arteriosclerosis and was having some heart attacks. At 5: 00 A.M. on February 6th he was seized with a severe attack and died almost immediately. His mind retained its pristine clearness to the end.

Throughout his career Dr. Howell's prime interest was research, though he never allowed that interest to interfere with the meticulous performance of his duties as teacher and as administrator. He was deeply but, to all appearances, calmly absorbed in his research problems. The conduct of his researches seemed unhurried, even when conversation indicated that interesting developments were imminent. Though research was the occupation that gave him his greatest satisfactions, one gains the impression from statements he has made that it was for him at the same time a discipline. Yet he never turned over any of the detail to others; he never at any time had a trained research assistant. Whatever turn a problem took, whether into physics, as when he was dealing with fibrin crystals, or into chemistry, as when cephalin and heparin were isolated, he acquired and carried through the necessary techniques. Even after his retirement he