

The Work and Environment of the PHYSICIST

Yesterday, Today, and Tomorrow

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The present article is the text of Dr. Kelly's after-dinner address at the banquet of the American Physical Society and the American Association of Physics Teachers in New York City, February 1, 1957. Dr. Kelly is president of the Bell Telephone Laboratories.

THE steady growth in understanding of the structure of matter and energy and of their interrelation that has resulted from the researches of physicists and of their predecessors among the natural philosophers, has been of increasing importance to mankind for the past few hundred years. However, until this century, there was small impact on society of the new knowledge obtained by these researches until very long after the new knowledge was obtained. Physicists were therefore remote from the scene of action, and the general public was indeed hardly conscious of them or of their profession. Their "action at a distance" permitted a remote and sheltered environment, sometimes characterized as an "ivory towered existence".

Almost at the turn of this century, the physicist's relation to society began to change, and with this, his environment is changing. The new knowledge that his researches make available is applied by industry and government, for the civilian economy and for national defense, with a steadily decreasing time lag. The growth in economic and military strength and in the quality of living of our people has become ever more dependent on the rates of acquisition of new basic knowledge in physics and chemistry and of its applications. Industry and the government are, therefore, of growing importance in the evolution of physics and in the lives of physicists. Physics and physicists have entered the laboratories of industry and government, and industry and government have entered the laboratories of the academic world with funds for plant and facilities and for support of research programs.

As I stated, this is a new phenomenon of our century. Its beginnings were timid and small, but its contributions have brought increasing support until today it is expanding at an alarmingly fast pace. Because of its rapid tempo the assimilation of its benefits is presenting our society with many problems. In contrast with the remoteness from events of the day of the natural philosopher of previous centuries and the lack of knowledge or interest in his findings by the general public, the physicist of today participates at the policy-making level in the problems of our society. The new knowledge from his researches is front page news of our daily press and the subject of editorial analysis and speculation by the press and current magazines. Here is tangible evidence that the ivory towered existence is no more and, like it or not, the physicist is in the midst of the fast moving currents of the day in our society.

The dynamic policies of Communist Russia in the postwar period have accelerated this trend. To build its

military and industrial strength rapidly, it has placed great emphasis on science and technology. It has emphasized these areas and relatively neglected other areas of its society, such as the quality of living of the large masses of people, as only an authoritarian state can do. Our country, as the leader of the free western world, has also emphasized selected areas of science and technology to best insure that through maintenance of our superior strength warfare and communist world domination be prevented. Physics, as perhaps the most rewarding science for this purpose, is at the very spearhead of our nation's effort to increase its economic and military might.

In my talk this evening I shall attempt to place this changing situation of physics and physicists in historical perspective. I shall also review present trends and the problems we now face because of the dynamics of our society's applications of science.

WHILE science may be said to have begun soon after the birth of civilization, it was not until the fifteenth and sixteenth centuries that it became completely rational. Previous to this period, the halting progress of the philosopher in winning an understanding of nature was attained through a mixture, in varying proportions, of rational thinking, often restricted by theological considerations, empirical practice, and magic. The statement by Leonardo da Vinci in the fifteenth century that "science begins with observation; if mathematical reasoning can then be applied, greater certitude may be reached but those sciences are vain and full of error which are not born of experiment, the mother of all certainty," might well be taken as a new charter for understanding nature. It is also one of the earliest clear statements of the scientific method of today.

The natural philosopher of the fifteenth through the eighteenth centuries was not only a scholar of the university but also of the landed gentry, clergy, physicians, soldiers, and lawyers. His work was individual, often in a laboratory in his home or place of business.

By modern standards, measurements were then crude and of limited accuracy. Instrumentation was simple and of relatively low cost. It was thus possible for a scholar from any profession or business to maintain his laboratory as a diversion from his normal activities.

Interchange of information was through correspondence, the casual meetings of informal groups, and, later in the period, a few organized societies, such as the Royal Academies of England and France. Contacts with

the industries to supply them with scientific knowledge were rare and of little significance. In fact, the industrial arts were still largely empirical and long intervals of time elapsed between the acquisition of new knowledge by the natural philosopher and its utilization by industry.

In the nineteenth century there was a great expansion of knowledge of nature made possible by the rational science and its methods that had been nurtured and developed by the philosophers of the previous few centuries. In physics a scope of understanding of energy and matter of such breadth was attained that by 1890 it seemed as though the main framework of physical knowledge had been put together and that little remained to be done but to measure physical constants to the increased accuracy represented by another decimal place. In fact, substantially this statement was made by Professor A. A. Michelson at the dedication of the Ryerson Laboratory at the University of Chicago in 1893.

Time does not permit, nor is it necessary for this audience, to enumerate the areas of new knowledge that this century added. Its increasingly analytical, quantitative and more precise research, accompanied by more complex and costly instrumentation, tended to restrict the researches in physics to the universities and institutional laboratories. Physical experimentation largely ceased to be a hobby of the cultured gentleman as it had been through the past few centuries.

The large body of new knowledge available for profitable application in industry, commerce, and the military in this century led to the development of schools of technology where application of science was taught. Engineering gradually became a profession and its division into the disciplines of civil, mechanical, and electrical engineering gradually evolved. The engineering graduate, entering industry or performing as a lone inventor, accelerated the industrial application of new knowledge and time intervals between availability and application decreased. Even so, a few decades often passed before new knowledge was applied. For example, commercial dynamos and motors were not available until some 30 years after Faraday's masterful experiments provided knowledge for their development. Marconi's wireless telegraph experiments were not performed until almost 15 years after Hertz had identified the electromagnetic waves predicted by Maxwell.

While the application of new scientific knowledge to industry expanded greatly and proceeded more rapidly than ever before in this century, the emergence of the engineer, trained in applied physics, provided a buffer between the scientist and the utilization of his findings. "Action at a distance" thus generally continued right down to the close of the century. This ended the period in which the natural philosopher and the physicist, his successor in our area of interest, pursued a leisurely and sheltered life, with ample time for philosophic contemplation, experimentation in an area of his choosing, writing, and periods of unscheduled leisure.

The large increase in the volume of research in the

physical sciences of the nineteenth century, with its accompanying increase in knowledge of nature's laws, brought about a division of the natural philosophy of the physical universe into that of physics, chemistry, and astronomy. No longer was it possible for one to have forefront knowledge and professional creative capacity across the entire range of physical science. Scientific societies as forums for presentation of new research findings and journals for their recording also multiplied and, of course, each of these societies and journals was generally concerned with only one of the new divisions of physical science.

The closing decade of the nineteenth century ushered in a completely new era in physics. In our century it has steadily flowered, extended its scope, and widened its areas of influence and application. Down to this very day, there is a constantly expanding stream of scientific investigation that brings ever more exact knowledge of the universe, its age, its methods of creation, and of the matter and energy that comprise it.

THE application of the new knowledge of this era to our society's daily life progresses at an increasingly rapid tempo. It is bringing an undreamed of richness and variety to man's living. With its application to warfare, it is also making our living ever more dangerous to the point that man's destruction of his civilization, if not his depopulation of this planet, is now recognized as an ever present danger. With the rapid diminution of the time lag in the application of new scientific knowledge, now bordering on the immediate, to the instrumentation of industry, commerce, and warfare, the physicist is becoming an ever larger component of the applications organisms of our society, in both the civilian and military areas.

The physicist of the new era turned his attention to the structure of matter and its interrelation with energy at atomic and subatomic levels. The new knowledge of subatomic structure and radiation provided immediate, new, and promising opportunities for applications in the civilian economy, particularly by those industries interested in applications of electricity. The engineer, who had carried the burden of advancing the technology of electricity for his industry, was not equipped for the research and development of the new physics of this era. His depth of training in science was too limited.

To meet this situation, two of our major corporations interested in electrical application, the General Electric Company and the Bell System, brought the first physicists into industry to establish new laboratories for research early in this century. Whitney, Coolidge, Langmuir, and Hull of General Electric and Jewett, Campbell, Arnold, Buckley, Nichols, and Wilson of the Bell System were the pioneers of these laboratories where industry first brought basic research in physics into its laboratories. Through this venture, it was hoped that the time interval between acquisition and application of new scientific knowledge would decrease and that the effectiveness of translation would be increased.

This pioneering venture initiated a chain reaction

that has continued with acceleration to this day. These laboratories grew in size and today are two of the world's largest industrial laboratories where physics is applied. Other industries in ever-increasing number brought physicists into their laboratories. There was a parallel induction of research chemists into industry in even greater volume, and of mathematicians, but in limited number until quite recently. This expansion of science in industry continued for the first four decades of the century at a gradual pace. The pure and applied science effort of the nation, now called research and development, attained a level measured in dollars expended of about 800 million by 1940. (The 1955 dollar is taken throughout as the unit of measure.) Approximately three-fourths was expended by industry and the remainder in academic and nonprofit institutions and government. The expenditure level was certainly not as great as \$100 million in 1900. There was at least an eightfold expansion in these forty years.

In 1940, the incidence of national defense preparations followed by World War II brought to a close the period of gradual peacetime evolution of the partnership of the academic and industrial communities in creative physics. It not only closed this period but ushered in a new one of great dynamics and momentum in which government enters the partnership. This new period of scientific application with its accompanying tempo, scope, and ever growing financial support was born of national need but was nurtured and grew to its huge dimensions only because of the large and highly rewarding new knowledge that the physicists' and other scientists' researches made available.

During the war period almost all the academic physical scientists and many from other areas of science were brought into the national effort of winning the war. In cooperation with the research and development organizations of industry and the military, there was developed an almost completely new instrumentation of warfare based on new scientific knowledge. Much of the new was actually used in warfare and made large contribution to our victory.

The evidence of the power of science in implementing warfare that the contributions of the period provided, brought national support for large expenditures for research and development as a means for increasing our military strength. Since in the closing years of the war research and development for warfare were preempting almost the entire scientific and technical strength of the nation, the expenditure level immediately after the war was materially reduced. The level of expenditures then rose steadily in the decade 1946-1955, until the planned level for the coming year is about \$2.4 billion—\$1.9 billion for the military and \$0.5 billion for the AEC (only in part military).

The power of research and development in implementing the civilian economy and its economic worth to an industry had already been demonstrated in the pre-war years by the success of the then established industrial laboratories. The contributions of science to warfare with its large volume of civilian application by-

product knowledge greatly strengthened the confidence of industrial leaders in the value of research and development. After the war, industry therefore continued the expansion of its laboratories and new ones were established in increasing number. Its expenditure with its own funds for research and development, exclusive of its expenditure of about \$1.5 billion under contract for the military, grew to somewhat more than \$3 billion by 1956.

THIS upsurge in research and development greatly expanded the nation's need for physicists. It is best illustrated by the large increase in number of PhD's awarded in physics in the period 1946-1955, when there were 3400. This is contrast with some 3000 awarded in the previous fifty years. Even with this very large increase, the demand is now much greater than the supply. This is also true for other scientists and for engineers entering development.

For industry and the government the inexorable laws of supply and demand have operated in sharply increasing the compensation levels for physicists. This is bringing about a long overdue correction of compensation levels for physicists and other scientists and engineers as well. In this respect it is good. However, the short-term effect on our strength in physics in academic institutions is bad. The universities cannot move salaries upward so rapidly because of inadequate resources. Academic strength in physics is thus being weakened through losing faculty members to industry and government, but perhaps even more so, in the long run, by the academic world's not holding its needed share of the young physicists of highest quality completing their doctorate training. This most serious situation can only be corrected through higher academic compensation. It must be corrected.

Even with the present, and I believe temporary, plight of academic physics that I have described, academic physics has thrived and greatly increased in volume in our country throughout this century and particularly in the past ten years. The number of universities with graduate schools and research programs in physics of high quality has increased at least fifteenfold in the past forty years. The fraction of time devoted to teaching is generally at a sufficiently low level that the graduate faculty staff member can give much time and energy to research. The recent large number of graduate students, while often presenting space and facilities problems, gives the able staff member wide scope for his research interest through the thesis work under his direction.

There is no question but that with the compelling values to our culture of physics, as well as all science, and the essentiality to economic and military strength of basic physics and the training to and beyond the doctorate level of an adequate number of physicists, our society is not providing adequate support. This unprecedented expansion in needs has been with us for only a decade. As a democracy our government can only meet new situations as they are understood by a

majority. This inescapably applies to the resources to meet this need, for because of their magnitude and the penalties to private accumulation of wealth of present personal income and inheritance tax system, the government is fast becoming the source for a major portion of the expanding volume of funds required.

Because of these unfunded needs we must not be blind to or lacking in pride of the great progress of the past decade. We have trained—and trained well—more physicists to the doctorate level in these ten years than in the previous fifty. While facilities are inadequate, they have been largely expanded and improved. Research in physics in our academic institutions has increased greatly in amount and has comprised a growing fraction of the additions to knowledge of all the physicists of the world.

The academic community is, and must continue as, the primary source of progress in basic physics as well as the place for training the ever growing number of physicists that our nation must have if its culture and its way of life are to endure. I am confident that adequate support will come. My only concern is that, in the competitive pattern vis-à-vis Russia, the rate of growth may be too slow.

LET us now turn to some of the particular aspects of the remarkable growth in research and development of this last decade and the physicist's participation in them. While the military research and development budgets have grown enormously, as I have described, most of the funds have been expended for applied research or development, design, and evaluation. In these areas, many men trained in physics have made large contribution. In our present technical education pattern, their presence in significant numbers in applied areas of these programs is essential. Unfortunately, engineering educators and the employers of their graduates in creative technology have been slow in recognizing that engineering training is inadequate in its time length—four years is too little—and even in its content, for not enough emphasis is given to physics, chemistry, and mathematics. Therefore, the deeply trained physicist is now a vital member of the development component of the technical creative operation.

However, the changes in engineering education for those entering development that are now in progress will in time make available enough engineers with training in depth in science that the need for basic physicists in development will decrease. As this occurs, the nation's population of physicists engaged in basic research will increase more rapidly. Such a trend is decidedly in the interest of our national strength in both the military and civilian areas.

Perhaps \$50 million—at most \$100 million—of the military budget is devoted to basic physics—the acquisition of new knowledge. A large fraction of this is expended in academic institutions and a few industrial laboratories. The laboratories operated by the military, in general, do not provide an environment where basic research can flourish and very few even attempt it.

While the Department of Defense and the Atomic Energy Commission (I shall soon discuss the AEC's research programs) are responsible for about 90% of federal research and development funds, the National Science Foundation and the National Bureau of Standards have an important place in the nation's basic physics.

The National Science Foundation is now in its sixth year. It is exerting increasingly constructive leadership in promoting federal support of basic science. Its leadership and programs are excellent. It is, however, largely a funds dispersing organization. It supports basic research in academic institutions and has a broad fellowship program. It is proving to be a good mechanism for channeling federal funds into basic research. While the appropriations by Congress have had a healthy growth, the Foundation's proven capacity justifies continuously increasing support.

The National Bureau of Standards maintains programs in basic physics of excellent quality. It provides qualified and dedicated basic research leadership. However, its funds are inadequate for its authorized functions and the outlook for any considerable expansion in the near future is not good.

The nation's program in nuclear science and technology, in which physics plays the leading role, presents many unusual aspects. These are having a profound effect on physics and physicists. We shall dwell on them in some detail.

Because of the compelling importance of nuclear phenomena to warfare and to the peacetime economy, our government has placed almost this entire area of science and its applications under top secrecy restriction and assumed the direct responsibility for a large part of the science and technology. The Atomic Energy Commission was established by the Act of 1947 to finance and administer the program. While I am aware of the criticisms of the Commission in the secrecy area—that secrecy classification has been too broad and relaxed too slowly—it is my conviction that the program has been, over all, admirably administered. A good balance has been maintained between basic science and technology. Large support has been given for facilities and programs for basic science not only at the national laboratories that the Commission established but also at many universities. The Office of Naval Research and more recently the National Science Foundation have also provided support, particularly for programs. The technology for the military and civilian areas has also been well supported and administered. National laboratories, operated chiefly by our more mature industrial companies, have done most of the work.

The progress in basic science and military and peaceful applications has been phenomenal. We have maintained world leadership. This has been made possible by the capacities of our scientists and technologists, the large financial support provided by government, largely through the AEC, and the wisdom shown in the organizational patterns in which the work is done. I am sure that all will agree that because of the tremendous cost of these programs, our progress would have been very

much less had they not received direct government support. This action of our government is a completely new phenomenon for a democratic society.

Russia has also given large financial support and emphasis to the three areas. It has developed large competence in them. Recently there is evidence that it may, temporarily at least, surpass us in the pure science area. It has given adequate financial support to permit the building of ultrahigh-energy particle accelerators essential to progress in nuclear understanding well beyond the energy levels of any of our accelerators in being or in construction. The financial needs of research in this area—perhaps the most challenging and important at the frontier of physics—have recently been examined by a panel of distinguished physicists at the request of the National Science Foundation. The panel concludes that the construction of the required ultrahigh-energy machines and the research programs employing them, will require annual expenditures reaching perhaps \$90 million within five years—approximately twice the present annual rate. This program is so vital to our progress in nuclear science and the maintenance of our position vis-à-vis Russia that I am confident the government will support it. The expanding scope of the program will demand a continuing increase in the number of physicists employed.

The military applications of atomic energy have been highly successful. The splendid blending of the basic nuclear science strength of the nation, its applied science and design strength with the best military thinking for application under the leadership of the AEC has permitted our nation to utilize its scientific, technologic, and military strength most effectively. Thus our leadership in atomic weapons has been maintained. Basic and applied physicists have and will continue to play a major role in this all-important area of national defense.

The programs in peaceful applications of atomic energy have also made great progress. Secrecy restrictions have been steadily narrowed and there is increasing participation with their own funds by interested industry. We have now arrived at the point where very large expansion of nuclear science and technology in industry can be foreseen. The rewards to our society and to the industries will be of huge proportions. Basic and applied physicists, in large numbers, will be required to staff these programs. Industry must build a capacity in basic research in nuclear science as well as in the technology of the many areas of application. The building of basic research capacity is of special importance for as industrial application expands, government may well not provide enough funds for the expanding needs for basic research. This gives promise of becoming the most rapidly growing area of research and development in industry during the next decade or so.

The character of the research in nuclear science has greatly changed the working environment of the physicist. Huge multimillion or billion volt accelerators and more recently atomic piles are required for much of the

research. The capital and operational costs of these machine systems are so great that many research projects must share, on a scheduled basis, access to the machine. Also many of the experiments involve so much of exact instrumentation preparation and almost simultaneous taking of large amounts of data that several physicists often work as a team on each research.

The necessary complexity of measurement facilities and the availability for purchase of many of them have relieved the experimenter of much of the manual work common to the physicist of even twenty years ago. Also the amount of financial support, in many areas, makes available more technical aid than formerly. The physicist has adjusted well to these changing environmental factors, some favorable and others less so. There is no general evidence of his loss of enthusiasm, of satisfaction, or of creativity; although without doubt the increasing communal or teamwork trends present grave problems of adjustment to some individuals.

WE shall turn again to the research and development of the nation's industrial laboratories and the place of the physicist there. The volume of industrial research and development, financed by industry, in the decade after the war increased from an annual expenditure of about \$600 million in 1946 to some \$3.0 billion in 1956, and its work under contract with the government increased from \$400 million to about \$1.2 billion in the same time. According to the National Science Foundation, about 60 per cent of the nation's physicists were in the laboratories of industry in 1954. A large fraction of them, in common with almost all physicists in military laboratories, are working in applied physics or development and not in basic physics.

Their presence in such large numbers in development is most essential. As I stated earlier, engineers, who occupy a large majority of the nation's professional positions in development, in general have inadequate training in science to carry the full development responsibility. However, it is contrary to the best interest of the nation's progress in science and its application for so large a fraction of its deeply trained physicists to be lost to basic physics, even though they are highly productive in the applications area. A change in the pattern of our engineering education that provides deeper training in science with a significant fraction trained to the doctorate level and all with a minimum training period of five years will lessen the need for physicists in development work.

While there is basic physics work of excellent quality in some industrial laboratories, its amount has increased in this decade of rapid expansion of applied physics all too slowly. Since there is national need for a larger volume of research in basic physics and since it can be of large economic value to corporations, certainly to 100 or so of the largest, it can be reasonably anticipated that basic physics in industrial laboratories will rapidly increase in the next few decades. Frankly, if this does not occur I have great concern about our position vis-à-vis Russia. Their society is rapidly expanding its

basic research. Most probably adequate financial support to match their growth in science will not be given to our academic institutions. Industry can provide the support and thus make a large contribution to national strength as well as to their own economic position.

Because of the relatively small amount of research in basic science in industry, there are many who hold the view that industry cannot provide a stimulating environment and lifetime careers in basic research. This view is refuted by the history of the few industrial laboratories that have maintained significant programs in basic research over a long period of time.

At the risk of appearing to exalt Bell Telephone Laboratories, I shall use it as an example of an industrial laboratory that has contributed significantly to new knowledge in physics over a long period of time and provided lifetime careers in basic research that have been rewarding to many physicists. Davisson's experimental verification of the wave properties of electrons in the 1920s brought him the Nobel Prize. Fletcher and Crandall and associates made large contributions to basic knowledge in acoustics. Ives made many contributions in optics. Becker pioneered in the physics of oxide-coated thermionic emitters. Southworth and Schelkunoff pioneered through theory and experiment in acquiring knowledge of properties of guided electromagnetic waves. McKeehan added greatly to our knowledge of ferromagnetism. All of them and many others in the 1920s and 1930s devoted substantially all of their time to research directed at new knowledge and understanding of physical phenomena. It was not necessary for them to become a part of management or of development operations as they advanced in years in order for them to gain recognition within the company and to receive adequate financial reward.

After the interruption of the war years, Bell Laboratories' basic physics programs were further strengthened and expanded. Great emphasis was given to solid-state physics, particularly of semiconductors and ferromagnetic materials. The semiconductor work initially led by Shockley, Bardeen, and Brattain, three recent Nobel Prize men, has contributed large areas of new knowledge and stimulated much basic work in other industrial and academic laboratories throughout the world. The physics of conduction of semiconductors has been clarified and their surface states have been studied theoretically and experimentally until the quantitative science of surfaces is now extending its scope into areas beyond these refractory metals.

Much has been added to knowledge in crystal physics. Large single crystals of previously not attained purities have been grown and studied. Diffusion constants of many elements into single crystals of germanium and silicon have been measured. Zone melting techniques for purification of metals and mass spectrographic techniques for determining exceedingly small amounts of impurities in refractory elements have been perfected.

Microwave resonance in solids has been given large and rewarding attention. Bozorth, Yaeger, Kittel, and

Galt have employed resonance techniques in studies of ferromagnetic metals and ferrites. Resonance in many paramagnetic materials has also been pursued. All of this has provided much new knowledge of electronic energy levels and interactions in solids. Thus a new spectroscopy of the solid state is evolving which furthers our understanding of metals, insulators, and ferromagnetic and semiconductive materials.

The microwave resonance work here and elsewhere has led to analytical speculation in many places of a new solid-state oscillator and amplifier called "maser". Professors Townes and Bloembergen have given rewarding attention to this area. Only a few weeks ago Scovil, Feher, and Seidel in our Laboratories, for the first time I believe, have succeeded in making a solid-state maser along the lines proposed by Professor Bloembergen which oscillates at 9000 megacycles with measurable power outputs.

The extent of basic physics, of which these examples are typical, at Bell Laboratories is indicated by the number of physicists engaged there in basic research. Of the some 250 physicists in the Laboratories, at least half of them devote their entire time to basic physics, in contrast with the applied physics of the others.

This dedication to basic research has been most rewarding to the Bell System and to our society generally. The application of the new knowledge by the Laboratories from these researches in physics and those in chemistry and mathematics as well has been the central element in the Laboratories' large contributions of the past 40 years to communications technology.

I am, therefore, on very firm grounds in my assertion that basic science can thrive in industry and is most rewarding to it as well as to our society. I am confident that its area will expand greatly in the decades ahead and that industry in time will make contributions to basic science in amounts comparable to those of the academic world. In the solid-state area alone, the dedication of our Laboratories to it in a relatively narrow area of solids with the large rewards to our industry that will result from the research findings foretells the potential rewards to all industry concerned with matter in the solid state when their laboratories pursue basic research in the solid state of sufficient scope in their areas of interest.

Looking to the future, there is increasing need for the physicist in basic physics in our society, and with the changes I have mentioned in the educational pattern of the engineer, the need for physicists in development should become relatively less. The academic world will continue to be the physicist's place of origin and his most stimulating environment. Industry, however, will provide an ever-expanding area for careers in research in basic physics. While the environment cannot be made in every respect as attractive as that of the university, it can be made so nearly the equivalent that a happy, stimulating, and productive life in basic physics can be foreseen for the evergrowing number of physicists whose careers will be in the laboratories of industry.