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Symposium

A foundation for research

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This happy occasion is a birthday celebration. It is a time for affectionate reminiscences and optimistic prognostications. It's a time to look back and a time to look forward—but most of all it's a time to sing Happy Birthday—off key or on.

It's a time to look at the stars—not at the budget. It's a time to chortle in our joy for surely this is one of Lewis Carroll's frabjous days. Callooh! Callay! It's a time for faith—for the belief that there are certain self-evident truths. Among these truths is this: research is a fundamental human activity—it illuminates and blesses our lives. Sure it helps to make a living but most of all it helps to make living worthwhile—culturally as well as practically. It's time to be an optimist—things cannot get worse; not a pessimist—things cannot possibly get better. Maybe I have that reversed—who cares? It's a Birthday Party. Happy Birthday, National Science Foundation. We salute your Board, your Director and, most important of all, your Staff.

Twenty-five years ago the challenge was direct and explicit. The National Science Foundation Act of 1950 authorized and directed the Foundation "To initiate and support basic scientific research . . . ." There were additional mandates but there it was, the American people, through their elected representatives, created *A Foundation for Research* and that is the title of this piece. It is not *the* foundation,—there are many other agencies and institutions in and out of government which support research. The word "foundation" is not used solely in terms of funding but more in its literal sense—the underlying structure on which all else rests. The word "research" is not qualified by the adjective "basic." In response to the pressures of our times, the Foundation was authorized to support applied research in 1968 by amendment of the act of 1950.

One hundred and one years ago in *Life on the Mississippi* Mark Twain wrote: "There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact." Those in experimental work may relish Twain's jibe, those in theory may resent it. Be that as it may, the answer to Twain is clear—research is the investment of fact, the investment which may lead, at first to healthy conjecture and speculation, but which ultimately leads to understanding and hopefully to wisdom.

The NSF has supported, encouraged, initiated, and counseled a fair share of the research investment in this country over the last 25 years in its many functions as *A Foundation for Research*. The NSF has other functions but here it seems appropriate to enquire into what return has this investment brought. This will be the burden of this tale. The choice of research returns to be discussed will be arbitrary but hopefully not capricious. The main subjects will be Earth Science, Molecular Science, Environmental Science, Astronomical Science, and Social and Applied Science. The word *Science* is used here because each of these subjects involves a number of scientific disciplines. For example, Earth Science includes geology, geophysics, geochemistry, and seismology. Molecular Science includes molecular biology, molecular chemistry, and molecular physics. Astronomical Science includes astronomy, astrophysics, and astrochemistry. The remarkable advances in pure mathematics, fundamental physics, and basic chemistry during the past 25 years will not be discussed and I can only beg your indulgence for the choice of subjects which led to these important omissions. Nonetheless the mathematician, the physicist, and the chemist know that his branch of science has been thoroughly involved. This piece is about the wood, not about the trees. It follows these foresighted words, and I quote:

"The complete solution of many research problems today requires the correlation of many individual viewpoints approaching the problem from several directions. The Foundation is acutely aware of its obligation to support integrated attacks upon borderline and interdisciplinary problems."

No, those words are not from yesterday's news release. They are from *The Second Annual Report of the NSF* for 1952.

This tale will range beyond the NSF role in the support of research dūring the past 25 years but some bias will be apparent. In telling this story there will be no mention of the names of individual investigators. On this day it would be more appropriate to name the program managers who chose the investigators. Anyhow as Seneca said, "the reward for a good deed is to have done it."

Earth Science

Where better to begin than here at home on the spaceship which we call earth? It is indeed our spaceship and it is the only possible habitat in the foreseeable future for the billions of human beings who ride it. Thus we are compelled to learn all we can about it, if we are to conserve and utilize its resources for the benefit and survival of man.

During the lifetime of the National Science Foundation the Earth Sciences have been revitalized by one of the most rapid, thorough, and potentially practical revolutions in the history of science. Instead of the fixed object which the earth appears to be, to one man during his lifetime, the earth has been shown to be an intricate mechanism with interlocking movements on a global scale which involve its surface and extend deep into the interior. This big picture, which goes under the name of continental drift, sea floor spreading, and plate or global tectonics, was put together from many sources, but a prolific one among these was the data gathered about the sea floor during the hundreds of seagoing expeditions sponsored by the Foundation. The Deep Sea Drill-

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ing Project, using the drilling vessel Glomar Challenger under NSF auspices, brought home to shore laboratories cores of oceanic sediments which verified and elaborated the new ideas.

For many years the concept of continental drift was an intriguing but controversial one. It did not gain wide acceptance because of many apparent discrepancies in the evidence and because of the lack of a reasonable driving mechanism. It all started with the fit of continental margins, especially the west coast of South Africa and the east coast of South America, but by now a number of other pieces of evidence have been brought to light.

First, *the matching of rocks between continents.* Detailed studies in northeastern Brazil and west Central Africa have shown that the older rocks in both continents are similar in composition, age, and structure.

Second, *fossils.* The finding of fossils of shallow water reptiles and amphibians in rocks over two hundred million years old in all of the southern continents, including Antarctica, argues strongly that these continents were once joined together. There is no other logical way for these animals to have spread from one continent to another.

Third, *rock magnetism.* The Earth's magnetic field periodically reverses, and on land a sequence of chronology of these reversals had been established for the past six or seven million years. About 15 years ago it was noted that the mid-Atlantic Ridge is flanked by magnetic anomalies that are parallel to the ridge, and symmetrical on either side. The pattern of anomalies on the west side of the ridge is virtually a mirror of the pattern on the east side. These anomalies are apparently also caused by the reversals of earth's field. Molten rock rises from the mantle along the mid-ocean ridges, cools, and acquires the imprint of the magnetic field at the time of cooling. More molten material forces the cooled material to one side and literally pushes the sea floor apart. As the sea floor spreads, the continents are carried along on plates in the earth's crust. Whether these plates are pushed by the outward motion of the sea floor from the mid-ocean ridges or pulled by downgoing slabs at the continental edges or dragged by convective currents in the mantle is still not perfectly understood.

Fourth, *seismology.* The earthquakes of the world are concentrated in belts or bands. These belts follow the mid-ocean ridges, the margins of some continents, and the deep trenches of the oceans. Detailed studies of the oceanic trenches, especially the Tonga Trench in the Pacific, show that depth of earthquakes gets progressively greater away from the trench, reaching down to 700 km. This suggests that as the crustal plates move away from the ocean ridges, they are also drawn down underneath the margins of the continents or in the deep trenches of the oceans and reabsorbed into the mantle.

Fifth, *the results of the Deep Sea Drilling Project.* If the concept of plate tectonics is correct, there should be no part of the oceanic crust that is more than about two hundred million years old and this part of the crust should be close to the continents and the trenches. Drilling across the mid-Atlantic ridge and in the Pacific has confirmed this. For example, the volcanic basement close to the mid-Atlantic Ridge is only a few million years old, but close to the eastern margin of the United States, for example, the volcanic rocks of the oceanic crust are about one hundred and sixty million years old.

This new unifying concept of global structure and tectonic processes provides a framework for new thinking and research into the mechanisms that shape the earth. Within this framework a deep understanding of earthquake phenomena has arisen which is of the greatest practical importance. First of all, the concentration of seismicity at the boundaries between plates explains the global pattern. There is much more in addition. By combining laboratory experiments on the fracture of rocks with field data, earthquake faults can be described in terms of empirical fracture mechanics and the radiation pattern of seismic waves can be predicted theoretically. Precursory phenomena prior to earthquakes have been detected and respectable seismologists around the world have now joined astrologers, mystics, and religious zealots in earthquake prediction. Put your bets on the seismologists—they may bring home a windfall of untold benefit to human society within the next decade.

Molecular Science

Three billion years ago our mother earth gave birth to life in its simplest form—a molecule which could replicate itself by using building blocks formed by random photochemistry in some aboriginal soup. Within the last million years or so those simple molecules have organized to form a living organism which can understand the molecules themselves and how the molecules build one gene, the unit of heredity, the key to replication and reproduction. This miracle of understanding has come into being over the last hundred years or so, but it is research in the last 25 years which has brought forth a dramatic and coherent picture of the fine structure of the gene, the genetic code, and the control of gene expression. A great synthesis of knowledge has resulted which has conceptually bridged the long-mysterious gulf between the world of the living and the non-living. This synthesis has led to realization of the continuity between inanimate and animate matter, based on the understanding of the potential for life, inherent in molecular organization.

Developments in molecular biology have been international in origin and in the United States there have been a number of supporting agencies. Many critical advances were made by NSF grantees. In retrospect it is fitting that the first Foundation award, Grant G-1, "The Effect of Hormones of the Anterior Pituitary Gland on Fatty Acid Metabolism," was in biology. In the infancy of the Foundation the story of the double helix model for DNA, the genetic material, was already known and it was also known that genes are arranged linearly on the chromosome. Early work supported by the Foundation provided the first proof that mutations within a gene also form a linear array and that mutations probably involved a single DNA nucleotide. This work laid the basis in part for the further development of molecular genetics.

In another grant program, the building blocks of DNA were put together into a predetermined sequence of groups of three, each of which is a code word. This collection of synthetic genes was then used to make a second molecule called messenger RNA. Messenger RNA, in turn, directed the synthesis of a protein-like chain. This new chain was then broken down, one by one, into its individual building blocks and each was identified. By identifying each of the building blocks of the new protein, it was possible to break the code of the original DNA and confirm that three nucleotides make one code word and specify a particular amino acid. It was also possible to establish the direction in which information of the messenger RNA is read, that punctuation between code words is unnecessary, and that code words cannot overlap. How is a particular amino acid positioned properly in the chain? The middleman in this process has been identified as another kind of nucleic acid, transfer RNA. There are different species of transfer RNA, each of which can recognize only one amino acid and a proper code word on messenger RNA. The primary structure of transfer RNA was determined in a Foundation-supported grant. Other work led to the realization that not all cells read a genetic message in exactly the same way and thence to the identification of the *stop* signals which mark the spot at which synthesis of proteins stops.

Environmental Science

The National Science Foundation has played the leading role in initiating comprehensive studies of extensive ecosystems. Although one view of ecology has always been synthetic and holistic, it was apparent in the early 1960's that most studies were not sufficiently comprehensive and quantitative to achieve more than a generally descriptive level. After years of modest support of Systematic Biology, NSF took a major initiative in supporting the Biome Programs generated under the International Biological Program. The investment in Systematic Biology began to pay off.

While it cannot be said that the attempt to construct a total system model has been successful, there has been considerable success in modeling component parts. The models developed in these studies have found surprisingly early use in addressing a variety of land management problems, simply because they are the first tools available for making reasonable projections of the consequences of management alternatives. Most important, however, it is clear that a new era has been initiated in which ecology will be more adventurous, more quantitative, and will direct more attention to the construction of mechanistic models for understanding and predicting the behavior of total systems.

Our immediate environment is the land, the sea, and the air, but the deep core of the earth produces a magnetic field around us which deflects penetrating particles from the far reaches of the Galaxy. Our environment is the Universe. One of the most important trends during the life of the Foundation has been the developing recognition, shared by scientists and the general public alike, that the environment is in fact a single entity, a gigantic system. Environmental Science is the study of all natural processes, their interactions with each other and with man. The Board and the Staff of the Foundation have been well aware of the many important problems such as the removal of sulfur from smoke, the recycling of industrial wastes, and the protection of open spaces and of the technological and institutional changes needed to change them, but they have also been greatly concerned about the advances required in the science of environmental systems if the basic knowledge and understanding needed to help resolve problems of public interest are to be provided.

Astronomical Science

And now we lift our eyes from the earth to the heavens—to the planets, the sun, the stars, and the interstellar medium surrounding them, the galaxies and the vast reaches of space and time. It goes without saying that in astronomical science in the past 25 years it has been the space adventure from Sputnik to Apollo which has captured the popular fancy. It goes without saying, too, that the National Aeronautics and Space Administration has played the primary role in this incredible human venture. At the same time, NSF has played a supporting role. For example, NSF funds built the mass spectrometer used in the strontium–rubidium dating of lunar rocks and soils which showed that the moon and the meteorites and inferentially the earth and the sun are the same age, approximately four and one-half billion years old.

Over this same 25-year period there has been a veritable explosion in astronomical science and here NSF has played an important and in many ways the leading role. Visual astronomy is thousands of years old and optical astronomy is 366 years old. Radio astronomy is 44 years old, but it has only been in the last 25 years that radio astronomy has become a mature science. Witness the development of Very Long Baseline Interferometry which gives us exquisite small details of the structure of enormous radio sources. Here NSF has played a major role. This same 25 years has witnessed full-scale extension of optical astronomy into the infrared and ultraviolet and the birth of microwave and molecular astronomy, x-ray astronomy, gamma-ray astronomy, and neutrino astronomy. In addition, cosmic-ray studies, no longer in the forefront of elementary particle physics, have become an integral and important part of astronomical science. We can now "listen" to the "music" of the spheres over many octaves and not just within one. The celestial message is borne not only by photons, but also by neutrinos and by energetic nucleons and nuclei.

In order to observe and detect over a wide range of radiation and particle energies, it is necessary to have observatories equipped with large telescopes or other detectors and sophisticated auxiliary instrumentation. Very early in the life of the Foundation it became clear that National Centers were necessary to meet national needs for research in astronomy and the atmospheric sciences requiring facilities, equipment, staffing, and operational support which are beyond the capabilities of private or state institutions and which could not appropriately be provided to a single institution to the exclusion of others. Unlike many federally sponsored research laboratories, the NSF-supported National Research Centers do not perform specific research tasks assigned by or for the direct benefit of the Government. They are maintained for the purpose of making available, to all qualified scientists, including their own staffs, the facilities, equipment, skilled personnel, and other resources required for the performance of independent research of the scientists' own choosing. This has all run parallel to NSF support of users' groups at the national accelerator centers built by the Atomic Energy Commission.

The Foundation supports four astronomy centers [National Astronomy and Ionosphere Center at Arecibo, Puerto Rico; Cerro Tololo Inter-American Observatory near Santiago, Chile; Kitt Peak National Observatory at Tucson, Arizona; and National Radio Astronomy Observatory (NRAO) at Green Bank, W. Va.] and one atmospheric research center [National Center for Atmospheric Research (NCAR) at Boulder, Colo.].

At the same time the Foundation has provided an increasing amount of research project and instrumentation support for ground-based astronomy in universities and other private institutions both national and international. New, up-to-date instrumentation is essential in research activities in all fields. Here the term ground-based must not be taken too literally. For example, the stratoscope balloon-borne telescope project, with NSF support, obtained pictures of planets and galaxies at the high resolution of one-tenth of an arc-second. NSF grantees have sent their instruments far and away in rockets and satellites. Today the Foundation supplies well over half of the total federal support of research in astronomy.

As mentioned before there is no point in parcelling out credit here and there. Rather it's the overall picture to which NSF has contributed its fair share which merits our attention, and what a picture it is. Our view of the universe has widened and deepened with astronomical discovery after discovery in the past quarter of a century. First of all consider the secrets wrung from observations of the interstellar clouds of gas and dust which permeate our galaxy. In 1951 came the discovery of the 21-centimeter line of neutral hydrogen, in 1963 the hydroxyl radical was observed, and in 1968–1969 the molecules of ammonia and water. Astrochemistry came into being. Approximately 150 lines from 33 different molecules, some with rare isotopes, have now been observed; 27 of these were first detected by NRAO telescopes. I'm glad to note that ethyl alcohol has finally been observed—I was beginning to wonder whether heaven was such a great place after all. But in all seriousness the interstellar medium is of the utmost importance to us not only because it is the site of the formation of stars like our sun but also because it contains the simpler organic molecules whose further build-up on planets may lead eventually to the development of life.

In his brilliant Robertson Lecture earlier today, Prof. Martin Rees spoke about the many exciting developments in astronomical science over the past 15 years. These include the discovery of galactic x-ray sources in 1960, quasars in 1963, the microwave background radiation in 1965, and pulsars in 1967. NSF research has played a major role in subsequent developments. In fact if I were to identify the astronomical National Centers with major contributions in one program only it would be quasars at Kitt Peak, pulsars at Arecibo, just as it has been molecules in space at Green Bank and solar physics at NCAR. An aside is appropriate here. Quasars represent the violent transformation of as much as one million solar rest masses into energy in the form of magnetic fields and relativistic electrons. Is it annihilation energy, nuclear energy, gravitational energy? We still do not know, and I for one believe that the solution of this celestial energy crisis, when it comes, will tell us something about energy generation and energy transformation of potential application to our terrestrial energy problems.

These exciting observational discoveries tend to overshadow the advances simultaneously made in our understanding of stellar evolution and of the nuclear processes associated with the various stages of that evolution. The realization during the 1950's that the red giant stage of stellar evolution involved helium burning which transforms helium into carbon and oxygen was just as far-reaching as the discovery in 1920 that the main sequence stage involves the conversion of hydrogen into helium. This fundamental understanding of the red giants has been followed by deeper appreciation of what occurs in the advanced stages of stellar evolution—in the variable stars, in the so-called horizontal branch, in the red super giants, in the blue super giants, in novae and planetary nebulae and in supernovae. The answers are not all in yet but the conceptual framework is there.

However, the rapid experimental and observational advances have not been completely assimilated theoretically. Some think there exists a crucial situation in our understanding of the physical universe and I cannot refrain from telling a story, if only to put my "gee whiz" attitude about astronomy in perspective. A friend of mine, who shall be nameless, takes it all very seriously and some time ago, working under an NSF grant, he wrote a paper entitled "The Developing Crisis in Astronomy." Sure enough, when the paper was published there was the tell-tale asterisk after the title referring to a footnote which read, "Supported in part by the National Science Foundation." Well, you can't win 'em all.

Social Science and Applied Science

In an entirely different context, in the story of the death of a young President, who earlier graced this Academy's centennial ceremonies, William Manchester wrote "Research, of course, is no substitute for wisdom." The "of course" is quite right. But let there be no misunderstanding. If we are to avoid the destruction of nature and the degradation of mankind, *we must learn how to transfer research into wisdom.* Social Science and Applied Science in different ways strive toward this goal.

Social Science was not included in the mandatory language of the NSF act in 1950 but research in the social sciences has been assisted since late 1953, beginning with subareas close to the mathematical, physical, and biological programs. The close bonds between the social and natural sciences have been since then one of the hallmarks of NSF activities.

Engineering Science has been part of the NSF program from the beginning. Engineering Science has aimed to increase the understanding of the principles and concepts which are common to and underlie a wide variety of technological problems.

Materials Research has been an NSF function since the beginning and the program was considerably augmented when the Foundation assumed the responsibilities for the Interdisciplinary Materials Research Laboratories from the Department of Defense in 1971.

Thus, a firm groundwork was laid in the social and applied sciences for the *Research Applied to National Needs* (RANN) program that was developed in response to the applied research authorization granted in the amended NSF Act of 1968. Starting with *Interdisciplinary Research Relevant to Problems of Society* (IRRPOS) in 1969, it was only necessary to sharpen and focus research on selected environmental and social problems and on opportunities for future technological development in order to respond to the legitimate demands of a society for which the fruits of research had been, speaking frankly, a mixed blessing. Basic to the concept of RANN from the beginning was the eventual transfer of programs to mission-oriented agencies of the Federal government and to industry. One example must suffice. Between 1971 and 1974 RANN led in the effort to define a solar energy research program to more fully understand and exploit this inexhaustible resource with which we are blessed. The payoff came at the formation of the *Energy Research and Development Administration* (ERDA) to which RANN was able to transfer funds, staff, and know-how in solar energy technology. At the same time RANN was able to continue with concentration on innovative, long-range, high-risk, high-payoff projects in solar energy research. NSF is indeed responding to national needs.

Conclusion

This has been one man's account of the return on the American people's investment in *A Foundation for Research.* There have been failures as well as triumphs, but those are for others to record. Research has enriched our lives and nurtured our livelihood but it has also brought inevitable problems which hopefully in these next years it can help to ameliorate. All in all it has been a twenty-five year success story with best of all, rich promise for the future. We will fulfill that promise only if we succeed in *transforming research into wisdom in the compassionate use of knowledge in the affairs of mankind.*

And so, in conclusion—once again, we salute you, National Science Foundation; Happy, Happy Silver Anniversary! You deserve this fervent wish. If there are any clouds in your future, may they all have silver linings.

There is little original in this tribute to the NSF. The words of many authors have been paraphrased or used almost verbatim where continuity permitted. My thanks are expressed to many members of the NSF staff for assistance in the assembly of background material for this talk and for editorial advice.