SCIENTIFIC AMERICAN

SEPTEMBER, 1953 VOL. 189, NO. 3

FUNDAMENTAL QUESTIONS IN SCIENCE

An issue devoted to science in its strict sense: the interrogation of nature. This introduction raises the question: Does our society confuse science with applied science, and thus neglect the former?

by Warren Weaver

It has become a custom for SCIENTIFIC AMERICAN to devote its September issue to a unified topic. The first of these special issues, three years ago, presented a review of the progress of science over the first half of the present century. Two years ago the subject was the human resources of the U. S., with special emphasis on scientific manpower. Last year it was automatic-control mechanisms. Under the title of "Fundamental Questions in Science," the present issue takes up another topic of wide public interest.

The unity of this issue has nothing to do with the subject matter of the various articles. Their authors deal with many fields of science—mathematics, astronomy, physics, biology, chemistry, psychology. They range over the heavens and the earth, the cell and the atom, man's mind and his ways of thinking. But these articles are nevertheless built around one central theme. It has to do with the motivation of the scientist, and with the true nature of free science.

Each of these articles is the reply of a first-rate and active scientist to one common query: "What question in your special field seems to you to be, at this moment in the development of science, a germinal question? What really interests you? What seems important to you? What do you like to think about?"

Do not be misled into brushing these questions aside as trivial. To the question "What is science?" the realistic answer, it has been said, is that science is what scientists do. And in the present scene, when a dangerous anti-intellectualism seems to be invading our society, and when pleasant temptations and unpleasant pressures divert scientists to "practical" researches, it would be still more meaningful to declare: What science *ought to be* is what the ablest scientists *really want to do*.

This may seem, at first thought, a shallow, hedonistic attitude, as though one were arguing that science should be merely a private entertainment for scientists. Actually free science, the free following of curiosity, has never been trivial, selfish or purposeless. The sober record of experience shows that the trained human mind, if you give it free play and a congenial climate, turns to deep and significant enterprises. The rational approach to life is a successful and productive approach. The most imaginative and powerful movements in the history of science have arisen not from plan, not from compulsion, but from the spontaneous enthusiasm and curiosity of capable individuals who had the freedom to think about the things they considered interesting.

The articles assembled here offer splendid confirmation of these claims. Their eight authors are concerned with great pivotal questions which go to the heart of our understanding of the structure of the physical universe, the processes of life and the nature of the human mind.

The first two articles are concerned with the way the physical universe is put together. What goes on within that tiniest of all mysteries, the nucleus of an atom? What has happened to the relatively tidy picture which we all had, not too many years ago, of a physical world built from only a couple of elementary particles? What sort of *reductio ad absurdum* are we headed for, when the number of elementary particles now stands at perhaps 20 and still tends to increase? Is it possible that these elementary particles have become neither elementary nor particles?

The next two articles go rocketing off to the other dimensional extreme of the universe, into questions about cosmic rays and galactic universes. For their explorations the authors use mental devices which have already penetrated farther into outer space than physical rockets can ever hope to go.

It is not uncharacteristic of modern trends in science that chemistry, in this series of articles, appears as the close companion of biology. A large fraction of present-day pure research in chemistry is either essentially indistinguishable from physics, or is intimately involved in the biological sciences. Thus we find chemistry here turned upon a truly cen-

tral and universal question of the life sciences: How do living things build the characteristic material out of which they are so largely constructed?

Moving still further toward the life sciences in the nowadays continuous spectrum of science, we find an article on one of the great central mysteries of biology—the problem of differentiation. A man's body starts as a single fertilized cell. Somewhere along the way it is arranged that certain of the cells arising from this common ancestor cell develop specialized characteristics and become nerve cells; certain others become liver cells, while still others develop into the cells of fingernails, hair, muscle, connective tissue, and so on. How does this specialization take place? Here, surely, is a deep problem which is at the very core of biological science.

The last two articles take up questions in the realm of the mind itself. One deals with the nature and mechanism of memory. The other is concerned with the foundations of the mind's logical processes and its judgments. The author analyzes two concepts of probability—the statistical and the inductive—and shows how we find the former useful *in* statements about concrete physical situations, while we seek, in the latter, a method for making judgments *about* such statements.

Viewing these articles all together, what do they teach us about the character of pure science? As responsible citizens of a country which still desires intellectual freedom, still respects originality and variety, still treasures curiosity and still profits from dissent—and we must believe this in spite of the narrow, selfish, stupid, angry little men who try today to frighten us into a contrary position—as responsible citizens who believe in the conquering power of the mind, what lessons do these articles have for us?

Note first what these papers have to say concerning the character of the really interesting and important questions

The Greeks of the Pythagorean school asked the question: What

which are investigated by pure science. From certain "practical" points of view, these questions must seem esoteric and utterly remote. The interior of the nucleus! The distant galaxies of the cosmos! How can an investigating committee ever visit these places and check up? The chemical happenings within a cell, the inner workings of man's mind, the cosmic rays of outer space! In the play of what market place are their attributes assessed? What do such researches cure, whom do they feed, how much money will they make, how many will they kill?

There are, I think, two main observations to be made. The first is that the questions are important in the first instance because they have depth and sweep, because they are esthetically attractive, because they are instances of man's mind seeking to meet the challenge of the universe. The second observation is that pure science is also intensely practical. The whole of man's experience has demonstrated that the practical results required for tomorrow depend essentially on the "impractical" free curiosity of today.

This latter point is one to which we in the U. S. have learned to pay a certain amount of lip service. But we have not yet really come to believe it in any operational sense. It is a truism that we are most ingenious, here in America, in instrumenting and exploiting ideas. But we are not so good as we should be in producing fundamental ideas. And we are still immature in the sense that we are impatient, that we demand quick "results." We do not furnish for science enough of the sustained and flexible support which would provide great minds with the leisure and the calm to think. We know that this is, in fact, the way to make important progress, but we lack the courage and the foresight to act on that knowledge.

This is a particularly relevant and timely consideration, now that the public is underwriting so much of the cost

ire the relations of the sides and the angles of a triangle?

Modern man, reflecting on the heavens and Einstein's unified field equations, asks: What are the relations of the forces of nature?

of scientific research. Major financing for science today is coming from the great national drives for funds for research on various disorders and, to a much larger extent, from various agencies of the government. There are, within all of these agencies for the public support of science, some wise and discerning persons who understand what kind of support science needs. They do not believe that the crowning triumph of civilization is a one-year grant of money carefully restricted to work on some rigidly specified problem; they know that really imaginative science does not come in the form of tightly scheduled reports, turned out in multiple copies, wrapped in cellophane and tied up with red tape. But there are too few such persons, and they receive far too little informed public support.

There are signs that our National Science Foundation is at last on its way to obtaining funds which will give it a chance to grow and develop. It has an appropriation of $8 million for the coming year, compared to $4.8 million last year. The ridiculous statutory ceiling of $15 million on its annual budget has been removed by Congress. It is to be hoped that the National Science Foundation will have the imagination, skill and courage to lead public opinion to a higher concept of what basic science is. Everyone knows that our free democratic society requires science for its defense, for the maintenance of its standards of living and for the health and comfort of its people. In a still deeper sense, however, our society requires science for its own intellectual and artistic worth. This must be more widely comprehended if we are to develop the climate of opinion and the techniques of support which will assure that science in America can be free and imaginative.

Basic science has aspects which make it at once attractive and forbidding to popular interest and understanding. The articles in this issue suggest to me certain pregnant words: *explanation*, *control*, *precision*, *enthusiasm*, *humility*, *mystery*. It will not be surprising if some readers consider this a queer group of words and a contradictory association of ideas. But science, as this set of articles well illustrates, has more of an artistic structure than some would have us believe, and it accommodates within itself a wide and actually contrasting set of ideas. "The great scientist,"
tralian medical researcher W. I. B. Beveridge has said, "must be regarded as a creative artist, and it is quite false to think of the scientist as a man who merely follows rules of logic and experiment."

What, then, is a truly scientific explanation? At the level of sophomore science, and almost universally at the level of general public discourse, one explains something by describing and analyzing it in terms of more familiar experience. This normally provides the illusion desired, for we seldom stop to think that the more familiar terms themselves require explanation. When one is talking at a fundamental level, however, explanation is a very different process. Familiarity ceases to be so useful, and the main requirements of an explanation, at this basic level, are compactness and generality. If you have a very compact (and hence often mathematical) way of stating relationships among a wide range of things and events, then you may say that you have explained them. The explanation need not be, and in fact almost surely is not, understandable in any ordinary sense. On the contrary, we must adjust ourselves to the notion that understandability, in this basic sense, is actually synonymous with compactness and generality and that we cannot ask for more.

Compactness and generality may offer less reassurance than the cozy explanation most of us originally look for. Esthetically and logically, however, they yield much deeper satisfactions. If we persist nonetheless in hankering for reassurance, perhaps this is to be found in another aspect of the scientific kind of explanation. Such explanations not only relate present data but make possible the prediction of future data. When a prediction is realized in actuality, then no end of comfort is available in the assurance that the theory works, that things are under control. It is this same control over nature that we carry over into the practical applications of science in technology.

The control which science gives us depends essentially upon the third aspect of science which I want to discuss. This is the precision of science, which is here most convincingly illustrated by the article on the forces that bind the atomic nucleus. Think, for just one sobering moment, of the incredible smallness which is involved. Roughly ten million atoms are required to stretch across the head of a pin. Yet if an atom were enlarged until it were as large as a house, its nucleus would then itself be about the size of the head of a pin. Science weighs this mite within a mite with an accuracy of one part in a million. Here is penetrating precision which is almost unbelievably exquisite. Yet, abstract as it is, it establishes a vast new industry, so powerful that we are not even permitted to know its size.

And lastly, what about those three words enthusiasm, humility and mystery? Enthusiasm we find everywhere in science; here, in these articles, we read such phrases as: ". . . so rich in form and function";
tions";
Humility we should find everywhere, as we do here: ". . . we cannot be sure"; ". . . especially hard to understand"; ". . . in deep water."
seems more characteristic of the great researchers in pure science than of those concerned with more applied and superficial problems. And mystery, although science continuously crowds it back, stubbornly and beautifully remains at the core. Necessarily, it confronts writers on fundamental questions at every turn: ". . . still remains the secret of the cell";
to answer [this question] as to tell where Sancho Panza's second donkey came from."
in specialization but that the central mysteries of nature continue to be its first concern, and there are hundreds of scientists investigating them today with the sweep and penetration exemplified in these articles.

The idea that science is coldly logical and faultlessly relentless in its forward march is contradicted by all that we read here. Science, as we find it in these articles, is no juggernaut, crushing all before it. Science here reveals itself as it truly is—a natural and integral part of man's whole life, an activity which, at base, is a blend of logic, intuition, art and belief. It has been refined into an instrument of great beauty and precision by the few, but this science of the few is merely the distillation of the experience of the many. As a natural social activity of man, science belongs to all men.

It is well for us that this is true. For it tells us that science need not be regarded as the possession of some select inner priesthood, but that its essential nature can be understood by all literate persons. This is the proposition on which Scientific American is based. This is the proposition which assures that the citizens of a free democracy, understanding and prizing the work of science, will provide the support and the terms of support that will cause science to prosper and bring its benefits, power and beauty to the service of the people.