results of this study are published in "A Review of Space Research," *Natl. Acad. Sci. Publ. No. 1079* (1962).

9. The report of the Rome IQSY meeting of the COSPAR Working Group on the IQSY was published in *COSPAR Bull. No. 14* (Mar. 1963).
10. The CIG–IQSY Committee, under the aegis of ICSU, is comprised of (i) officers who also make up the Bureau of the committee and represent the four international associations concerned with IQSY—W. J. G. Beynon, president (International Scientific Radio Union); M. A. Pomerantz (International Union of Pure and Applied Physics), N. V. Pushkov (International Union of Geodesy and Geophysics), and G. Righini (International Astronomical Union), vice presidents; and C. M. Minnis, secretary; (ii) members for administration, finance, and publication—D. C. Martin and H. Odishaw; (iii) discipline reporters—W. L. Godson (meteorology), J. O. Cardús (geomagnetism), D. Barbier (airglow), J. Paton (aurora), W. Dieminger (ionosphere), R. Michard (solar activity), S. N. Vernov (cosmic rays), M. Nicolet (aeronomy), and H. Friedman (space research); (iv) representatives of other interested scientific committees and organizations—F. Jacka (Scientific Committee on Antarctic Research); J. Blamont and Z. Svestka (COSPAR); A. H. Shapley (International URSIGRAM and World Days Service); and O. M. Ashford (World Meteorological Organization); (v) members for data interchange—V. Burkhanov, H. Odishaw, and T. Nagata; (vi) members for geographical representation—S. Manczarski (Europe–Asia region), K. R. Ramanathan (Indian region), A. Onwumechelli (Africa) and J. Roederer (Latin America); and (vii) ex-officio members—J. Van Mieghem, secretary general of ICSU; G. Laclavere, secretary general of CIG; and P. J. Beaulieu, executive secretary of COSPAR.
11. Members of the U.S. Committee for IQSY, established by the National Academy of Sciences, are R. G. Athay (solar activity), J. W. Chamberlain (aurora and airglow), H. Friedman (aeronomy), J. Kaplan (member-at-large), W. W. Kellogg (meteorology), P. Meyer (cosmic rays), H. Odishaw (ex officio), M. A. Pomerantz (chairman), S. Ruttenberg (executive secretary), M. A. Tuve (ex officio), E. H. Vestine (geomagnetism), and A. H. Waynick (ionospheric physics). Robert Fleischer, of the Office of Atmospheric Sciences, is NSF coordinator for IQSY.

Communication and Comprehension of Scientific Knowledge

Robert Oppenheimer

The theme that has been assigned to me seems in some ways a little odd. That is only in part because this talk comes after 3 days and 15 lectures in which, as actors and auditors, we have lived with many beautiful examples of good communication, and even very largely good comprehension—good understanding—of scientific knowledge. If I have any doubts, it may be that here and there, in those reports which dealt with subjects close to me, the communication and the understanding have gone a little bit beyond the knowledge.

In an important sense, the sciences have solved the problem of communicating within and with one another more completely than has any human enterprise. I may retell an old story. Thirty-five years ago, Dirac and I were in Göttingen. He was making the quantum theory of radiation, and I was a student. He learned that I sometimes wrote a poem, and he took me to task, saying, "In physics we try to say things that no one knew before in a way that everyone can understand, whereas in poetry. . . ."

It is an old and consistent tradition with us to be concerned with the words we use, and with their purification, and thus with the concepts in terms of which we describe nature. It was true of Newton, of Lavoisier, of Cauchy, of Mendel, and of course, in our day, of Einstein and of Bohr. As for Newton, we will understand this better when we have, after almost three centuries, the critical edition of the *Principia*; at least we will know that in the renowned *"Hypotheses non fingo"* it is not the first word but the last that bears the meaning.

When we tell about our work, we explain what we have done and we tell what we have seen, whether we are describing a radioastronomical object, or a new property of fiber bundles, or the behavior of men attempting to solve problems. We are prepared to believe that the explicit content of science has its roots in these accounts of action, often factual, often foreshortened and synoptic, because cast in terms which the scientific traditions have established long ago.

Among us there is surely a great and appropriate variation in how we describe this foundation for the objectivity of our knowledge, and for the lack of ambiguity in the terms we use to tell of it; and of course there is an even wider latitude, insofar as we may bring ourselves to speak of them, in what we think of the reasons for the success of science, in what attributes of the world of nature in which we find ourselves underlie the manifestations of order which are our business: why we can work on the same table and with the same test tube when we cannot have the same melancholy or the same resolution; why so much of the order of the natural world finds its expression in number and the more abstract mathematical structure.

We probably all, with varying enthusiasm, would say *yes* to Charles Peirce as to *how to make our ideas clear*. We would make a good case that we do indeed know the structure of some ribonucleic acids, or some properties of the longer-lived particles of physics, only leaving room for the fact that in new things as well as in old, there are points we may not have looked at, and that wonders may be hidden in the crevasses.

This foundation for knowledge precludes much that is an essential part of man's life. One cannot be a very effective scientist if he is a practising solipsist. We cannot expect to describe a common world of introspection by telling people what we have done and what we have seen; though probably we can, and increasingly we will, describe elements of behavior which may have some correspondence to the inner world. Among these things of which we cannot talk without some ambiguity, and in which the objective structure of the sciences will play what is often a

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very minor part, but sometimes an essential one, are many questions which are not private, which are common questions, and public ones: the arts, the good life, the good society. There is to my view no reason why we should come to these with a greater consensus or a greater sense of valid relevant experience than any other profession. They need reason, and they need a preoccupation with consistency; but only insofar as the scientist's life has analogies with the artist's—and in important ways it does—only insofar as the scientist's life is in some way a good life, and his society a good society, have we any professional credentials to enter these discussions, and not primarily because of the objectivity of our communication and our knowledge. But if I doubt whether we have a special qualification for these matters, I doubt even more that our professional practices should disqualify us, or that we should lose interest and heart in preoccupations which have ennobled and purified men throughout history, and for which the world has great need today. Your lives attest this.

This account of a constant concern within the scientific enterprise to purify and refine our language is, of course, a sort of parody of what we are all about. We do not really do this except in moments of crisis, or in order to make way for something very new and deep. We come to our new problems full of old ideas and old words, not only the inevitable words of daily life, but those which experience has shown fruitful over the years. This is an inevitable approach to the new; and when it is not too new, it gets by. But the comprehension, the understanding of scientific knowledge is a very different thing from being the recipient of a communication. I think there is an element of action inseparable from understanding: to question, to try, to apply, to adapt, to ask new questions, to see if one understands, and to test what one has been told: action in the laboratory or the observatory, or on paper, or, at the very least, in the motions of the spirit. We need, at times, to talk about the sources and the springs of this motion, without which communication would provide the fuel pipes, the electrical wiring, the transmission of a car, but not the combustion which gives it power and life.

We do not talk of this very well; imagination, play, curiosity, invention, action, these are all involved. They are indeed only rarely all combined, and supplemented by skepticism and criticism, in any one man in any one moment; one of the charms of the scientific enterprise is how deficient we can be in many of these qualities and still play some meaningful part in it.

We know that we love the old words, the old imagery, and the old analogies, and that we keep them for more and more unfamiliar and more and more unrecognizable things. Think of "wave," "information," "relativity." We know that one can explore and study the springs of the movement of science, that it is a fit if very difficult subject of study. Today at least we are not able to talk about it very well, not at all as we can of molecules or galaxies, or even of the effective definition of the words that we use. Yet we may be sure that without a living engagement there is no understanding and there is no life of science, and we know that we cannot command this, or perhaps even learn it, except by apprenticeship, by following what others have done, and by listening to the mischievous voices of adventure and play and exploration and doubt with which we greet a new experience or a new communication. This has very much to do with what we can in practice and honestly mean by the unity of science. I think, for instance, of contemporary mathematics, whose absence from this program does not at all reflect a lack of vitality, of discovery, and of beauty in the current scene. Up to our time, it has been the experience of our enterprise that there have been a good number of men who combined creation and wide knowledge of the mathematics of their day with a lively interest in those elements of the natural sciences in which this mathematical order might be embodied. This conversation, as a lively mutual understanding, is rather thin today. It is not rare to find a physical scientist who will hear some beautiful new result—in algebra for instance, or topology—with pleasure, with amazement, and with admiration; but it is not likely that he will be deeply engaged, and try to see if he can make it wider, how it affects other things he may have known, or thought to know. I know that it is also true that many mathematicians will accept with a certain interest that there are in nature two neutrinos which have different properties, or that astronomers believe that they may be witnessing evidence of very massive gravitational implosion in other galaxies. To me it seems good that we still do tell each other these pieces of news; but I would hope that the century-long tradition of a felt sense of reciprocal relevance between mathematics and natural science would soon again find itself embodied in many of us, or, far more plausibly, in our successors.

Thus between us, as specialists in our professions, there is a partly accidental quality to the effectiveness of our converse with one another, and thus to the effective unity of our view of the world, even as scientists. There are two reasons for deploring this. One is that past experience suggests so strongly that among the sciences there are elements of relevance and mutual enlightenment which make such converse an essential part of deep and rapid progress; the other is that we regret for ourselves what we do not really know, and we regret for others what we cannot really tell them. This is, of course, a reflection, within the internal society of the scientific enterprise, of a situation that characterizes our relations with human societies as a whole, with the society within which we are embedded, and that leaves us with problems, some very grave, and by no means all clearly soluble, having to do just with the communication and comprehension—understanding—of scientific knowledge.

These problems rest, of course, on human weakness and limitation; but more specifically they rest on at least three features of the scientific enterprise which it has in common with the world in which its whole action takes place: size and saturation, growth and change, and specialization. I will not speak to size, having no true wisdom as to whether there is a natural and appropriate limit to how vast the scientific enterprise can and should be, beyond which it suffers too deeply from suffocation and fragmentation. I do not think that I know an answer, but I rather hope that those who follow me today may have some wisdom; and I know that they have some views on how large our world should be, perhaps because that is a still harder question.

One thing we do know: growth and change imply size, and growth and change are very deep in the nature of the scientific enterprise. Without them we would not recognize the rooms in which we were living, or what our days were all about. As for specialization, it is what sharpens our tools and our words, and is the instrument for penetrating deeper and farther into the world of nature.

I think that we must live with these,

and that we can live with them. Some of us will know one thing, some fewer will know many things, and the unity of our knowledge, its freedom from contradiction, and its important and often very deep common relevance, will not preclude but will be enriched by the great and blessed diversity of man.

These limits on the communication and comprehension of scientific knowledge which we find among ourselves, with which we have been living and will continue to live, have their analogies in the related but vaster limitations that we have in our external relations with those who are not yet, or not ever, involved in the scientific enterprise. The first of these is with the young, those who may be entering the life of science, and perhaps also, perhaps even more importantly, those who may not. I cannot speak with even a decent record of experience or authority of the problems of education and schooling, for I have known them only at the late level that is essentially apprenticeship, where a young man or woman has become engaged in some part of science, and the problem is to help him enlarge his interest and his power and his knowledge of what others have done. I have the impression, which I hope may be true enough to be shared by most of you, that in the graduate schools, and in their increasing postdoctoral studies, we have in the natural and mathematical sciences rather happy arrangements for this period of apprenticeship, happy in comparison with the situation in other branches of study—historical or philosophical, for instance—rather happy in comparison with our sister institutions abroad, and very happy indeed in comparison with our own country some 50 years ago. Apart from this, my life gives me no qualification except to express an appreciation to our many colleagues who have been studying and practising the teaching of the sciences in the schools and the colleges, so that first sight shall not repel, and the institutions not resist the natural curiosity and love and joy of the experience, but open it, so that as many as can will have an opportunity to discover some trait of nature, to see with welcome some sure sign of order in nature, with their own hands and their own heads.

I know that our colleagues understand the universal value, in all teaching, of quickly correcting error. I know that they are concerned to free the teaching of science of a slovenly and lazy dependence on history, in which discoveries were often made in obscure, contingent, and not deeply relevant struggles, whose interest as history is not helpful to the young student, and usually obscure to his teacher. I know that they hope, as often as may be, to open perspectives on the larger connections in nature and in the sciences which describe it, and rarely, when it can be done with historical scruple, on some chapters in the history of man's knowledge.

We mostly take it for granted, though it is not quite obvious, that we would like to have this opening of the world of science, this induction into it, effective not only for those who will be of our company, but for as many as may be of all the young, and the newly young who are willing to study. It seems to me that there are probably two reasons why we hold this view, not in the first instance commensurable reasons. On the one hand I think we increasingly feel the need for companionship and for help. I am not here speaking of the patronage of science, which has not been ungenerous or niggardly in the past years, though it may come to be so. I have in mind rather what we all know, that more rapidly than ever before, the sciences have been embodied in new technologies, and that these bring on the scene new powers and possibilities, now a new need, now a new opportunity. These needs and opportunities often are relevant to what in us, and in most men, are the most deeply held convictions of what is right and good, convictions rooted in a long tradition, and integrally a part of our sensibility. We do not talk about it much, but most of us, I think, are committed to preserving life and health where that is possible. Increasingly, and largely because of the effects during the last centuries of technology and industrialization themselves on its modes, we are committed to limiting, if possible to eliminating, war. We are committed to relieving, to reducing labor and drudgery, and not only the hard labor of the field and the mine and the galley, but the dull labor of the Midlands factory. We are now clearly engaged in a great enterprise testing whether we can live in a world in which war does not play its traditional part, an enterprise in which not only long-inherited human institutions, but even older, even other more permanent human attitudes, of anger, hatred, solidarity, self-importance, righteousness, which war has fed, can permit the change. We are in this too deeply, I think, to let the good news or the bad news of the day or month or year affect or limit our hope and, where it is possible for us, our engagement in this great, open, unsettled action of man's history.

With the preservation of life too, and along with it the alteration and automation of work, we are concerned not only with the inadequacy of our institutions, which were framed for a very different world, but with our attitude toward the meaning and value and nature and quality of human life, so largely in our past built on productive work as its foundation. Here in this country we see the mixed fruits of medical and engineering technology first with the young and the old. It is reasonable to expect that they will spread, and that they will characterize many other technologically developed societies. I know of the concern, so well expressed by some of you, that even the saving of children's lives may have created problems with which no one can cope, that have some bearing on the growth and size of the human society.

Though I do not suppose that a thorough knowledge of science, which is essentially unavailable to all of us, would really be helpful to our friends in other ways of life in acting with insight and courage in the contemporary world, it would perhaps be good if in talking with them we could count on a greater recognition of the quality of our certitudes, where we are dealing with scientific knowledge that really exists, and the corresponding quality of hesitancy and doubt when we are assessing the probable course of events, the way in which men will choose and act, to ignore or to apply, or make hypertrophic or nugatory the technological possibilities recently opened. I think that some honest and remembered experience of the exploration of nature, of discovery, and of the way in which we talk to one another about these things, might indeed be helpful; but that is because it would remove barriers and encourage an effective and trusting converse between us, and make more fruitful the indispensable role of friendship. These things are perhaps always easier in a small society. They were perhaps easier a century ago, for us and for many of the countries of Europe. We have a modest part to play in history, and the barriers between us and the men of affairs, the statesmen, the artists, the lawyers, with whom we should be talking, could perhaps be markedly reduced if more of them

knew a little of what we were up to, knew it with pleasure and some confidence; and if we were prepared to recognize both the important analogies between what moves us to act and to know, and the extraordinary and special quality of our experience and our communication about it with one another. I have often thought that with the historic game so grand and so uncertain, we should not dismiss any help, even of that small part which we could play.

The other set of reasons for hoping that young people who will not be professional scientists, and older people who are young in heart, could have a greater scientific literacy and some limited experience, as ours also is limited, is that we know, all of us, that the experience of scientific discovery is a good and beautiful experience, and an unforgettable one. We know that this is true even of little discoveries, and we understand that with the great ones it is shattering. It was on his 71st birthday that Einstein said to me, "When it has once been given a man to do some sensible things, afterwards his life is a little different." It seems not really an act of arrogance but simply human, and not in the purely pejorative sense of the word, to wish these pleasures for as many of our fellows as can have them.

In our world, many things that men do rather naturally, that they have learned to do long, long ago, have become professions, have become part of the market. I think of song and sport and the arts, the practical arts and the fine arts. None of these is without discipline; and although they are very different from those that lead to the sciences, I would be slow to rate them easier. Yet people sing and make sport and practise the arts quite apart from the market, quite apart from a career. It would be a poorer, thinner life without that. Though surely we will not all burst into song, or take to skis, or pick up a chisel or a brush, some of us have done some of these things, and some of us will; and it seems a proper hope that in our education, both for the young, and for those, in growing number, who like us have kept a lifelong taste for it, we do what we can to open the life of science at least as wide as that of song and the arts. Not everybody will want our pleasures, as among us not everyone can taste the other's, and as even we cannot expect an astronomer and a biologist fully to share what each has. We think of this as a high and lovely part of life which, with all its discipline, is still directly responsive to a deep human need. We all know this, and all share it; but each of us, I think, must be free to use his own words to sing its praise, even to describe it.

We may be seeing a time in which war will come to play a smaller and an increasingly trivial part in man's life. I hope that we are. We may be coming to a time in which for growing parts of the world the production of goods will require a much more minor commitment of human effort and life, and the market leave men with a far greater measure of freedom. I hope that we are. For this it will clearly not be enough that we preserve the integrity of our communication and comprehension, either among us, or with our fellows; but this is at the heart of our enterprise, and it is the least we can do.