The Meaning and Limits of Exact Science

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EXACT SCIENCE—what wealth of connotation these two words have! They conjure up a vision of a lofty structure, of imperishable slabs of stone firmly joined together, treasure-house of all wisdom, symbol and promise of the coveted goal for a human race thirsting for knowledge, longing for the final revelation of truth. And since knowledge always means power, too, with every new insight that man gains into the forces at work in nature, he always opens up also a new gateway to an ultimate mastery over them, to the possibility of harnessing these natural forces and making them obey his every command.

But this is not all—or even the most important part of it. Man wants not only knowledge and power. He wants also a standard, a measure of his actions, a criterion of what is valuable and what is worthless. He wants an ideology and philosophy of life, to assure him of the greatest good on earth—peace of mind. And if religion fails to satisfy his longing, he will seek a substitute in exact science, I refer here merely to the endeavors of Monism, founded by outstanding scholars, philosophers, and natural scientists, a school of thought which commanded high respect only as recently as a short generation ago.

Yet, in these our days hardly a word is being heard about the Monists, although the structure of their ideology was unquestionably erected to endure for a long time to come, and it started out on its career with high hopes and great promises. There must be something wrong somewhere! And in fact, if we take a closer look and scrutinize the edifice of exact science more intently, we must very soon become aware of the fact that it has a dangerously weak point—namely, its very foundation. Its foundation is not braced, reinforced properly, in every direction, so as to enable it to withstand external strains and stresses. In other words, exact science is not built on any principle of such universal validity, and at the same time of such portentous meaning, as to be fit to support the edifice properly. To be sure, exact science relies everywhere on exact measurements and figures, and is therefore fully entitled to bear its proud name, for the laws of logic and mathematics must undoubtedly be regarded as reliable. But even the keenest logic and the most exact mathematical calculation cannot produce a single fruitful result in the absence of a premise of unerring accuracy. Nothing can be gained from nothing.

No phrase has ever engendered more misunderstanding and confusion in the world of scholars than the expression, "science without presuppositions." It was coined originally by Theodor Mommsen, and meant that scientific analysis and research must steer clear of every preconceived opinion. But it could not mean, nor was it intended to, that scientific research needs no presuppositions at all. Scientific thought must link itself to something, and the big question is, *where*. This question has occupied the minds of the most profound thinkers of all epochs and all nations, since time immemorial, from Thales to Hegel, setting in motion all forces of man's imagination and logic. But it has been demonstrated again and again that a final, conclusive answer cannot be found. Perhaps the most impressive proof of this negative finding is that until now all attempts have failed to discover a world view uniformly acceptable, in its general features at least, by all minds capable of judgment. The only conclusion which this fact permits, according to every dictate of reason, is that it is absolutely impossible to place exact science in an a priori manner on a universal foundation possessing a fixed and inclusive content.

Thus, at the very outset of our quest for the meaning of exact science, we are confronted by an obstacle which must be a disappointment to everybody who is seriously striving for knowledge. In fact, this obstacle has driven many a critically disposed thinker to join the ranks of the skeptics. And a no less regrettable fact is that there are perhaps just as many, or even more, individuals of the opposite disposition whom the fear of falling victim to skepticism—an ideology which they consider intolerable—drives to look for salvation from prophets of creeds like, for instance, anthroposophy. Such prophets appear on the scene in all epochs, not excepting our own, with their brand new message of salvation, and they often succeed, with an amazing rapidity, in gathering a following of enthusiastic disciples, eventually to make their exit from the stage and to sink back into the all-engulfing abyss of oblivion.

Is there a way out of this fatal dilemma? And where can it be found? This is the first question to claim our attention. I shall attempt to show that there is a positive answer to it, and that this answer will cast a light both on the meaning and limits of exact science. I submit to the judgment of each of you the validity of my proposed resolution of the problem.

I

If we seek a foundation for the edifice of exact science which is capable of withstanding every criticism, we must first of all tone down our demands considerably. We must not expect to succeed at a stroke, by one single lucky idea, in hitting on an axiom of universal validity, to permit us to develop, with exact methods, a complete scientific structure. We must be satisfied initially to discover some form of truth which no skepticism can attack. In other words, we must set our sights not on what we would like to know, but first on what we do know with certainty.

Now then, among all the facts that we do know and can report to each other, which is the one that is absolutely the most certain, the one that is not open even to the most minute doubt? This question admits of but one answer: "That which we experience with our own body." And since exact science deals with the exploration of the outside world, we may immediately go on to say: "They are the impressions we receive in life from the outside world directly through our sense organs, the eyes, ears, etc." If we see, hear, or touch something, it is clearly a given fact which no skeptic can endanger.

To be sure, we speak also of illusions, but never with the intention of implying that the sense perceptions involved are incorrect or even questionable. For instance, when a person happens to be deceived by a mirage, the fault lies not with his perception of the visual image, which is actually present, but in his inferences which draw false conclusions from the given sensory data. The sensory impression is always a given fact, and therefore incontestable. What conclusions the individual attaches to it, are another story, which need not concern us for the time being. Therefore, the content of the sensory impressions is the most suitable and only unassailable foundation on which to build the structure of exact science.

If we call the sum total of sensory impressions "the sense world," we may state briefly that exact science issues from the experienced sense world. The sense world is that which, so to speak, furnishes science with the raw material for its labors.

However, this seems to be a very meager result. For the content of the sense world is, in any case, only something of a subjective character. Every individual has his own senses, and in general, the senses of one individual are quite different from those of another, whereas the aim of exact science is to achieve objective, universally valid knowledge. It may seem, therefore, that in adopting our present approach we have been following the wrong track.

But we must not jump to conclusions. For it will become manifest that considerable progress can be made along the line of advance now open to us. Considered as a whole, the matter reduces itself to the fact that we human beings have no direct access to the knowledge conveyed to us by exact science, but must acquire it one by one, step by step, at the cost of painstaking labors of years and centuries.

Now, if we examine the content of our sense world, it obviously falls apart into as many separate fields as we have sense organs—there is a field corresponding to sight, another to hearing, and still others corresponding to the senses of touch, smell, taste, and heat. These fields are totally different from each other, and have initially nothing in common. There is no immediate, direct bridge between the perception of colors and the perception of sounds. An affinity, such as may be assumed by many art lovers to exist between a certain shade of color and a certain musical pitch, is not directly given, but is the creation, stimulated by personal experiences, of our reflective power of imagination.

Since exact science deals with measurable magnitudes, it is concerned primarily with those sensory impressions which admit of quantitative data—in other words, the world of sight, the world of hearing, and the world of touch. These fields supply science with its raw material for study and research, and science goes to work on it with the tools of a logically, mathematically, and philosophically disciplined reasoning.

II

What, then, is the meaning of this work of science? Briefly put, it consists in the task of introducing order and regularity into the wealth of heterogeneous experiences conveyed by the various fields of the sense world. Under closer examination, this task proves to be fully consistent with the task which we are habitually performing in our lives from our earliest infancy, in order to find our way and place in our environment. This is a task which has kept man busy ever since he first began to think at all in order to be able to hold his own in the struggle for existence. Scientific reasoning does not differ from ordinary everyday thinking in kind, but merely in degree of refinement and accuracy, more or less as the performance of the microscope differs from that of the naked eye. The truth of this statement, and that it must necessarily be so, is evident from the very fact that there is only one kind of logic, and, therefore, even scientific logic cannot deduce anything else from given presuppositions than can the ordinary logic of untrained common sense.

We shall therefore obtain an intuitively clear understanding of the results which science achieves through its labors, if we take our point of departure from the experiences known and familiar to us from daily life. If we review our own personal, individual development, and consider the point which our world view has gradually reached in the course of the years, we can say that we are trying to use the facts of experience as the foundation for a unified, comprehensive and practically serviceable picture of the world in which we live; that we conceive the outside world as filled with objects which act on our various sense organs, thus producing our different sensory impressions.

However, since this practical world picture which every human being carries within himself is not a directly given notion, but an idea elaborated gradually on the basis of facts of experience, it is possessed of no final character. It is changed and adjusted by every new datum of experience, from infancy to adulthood, first at a quicker, then at a slower pace. The same principle applies to the scientific world picture. The scientific world picture or the so-called phenomenological world is also not final and constant, but is in a process of constant change and improvement. It differs from the practical world picture of daily life not in kind, but in its finer structure. It is to the world picture of daily life approximately as the world picture of the adult human being is to the world picture of the human child. Therefore the best start toward a correct understanding of the scientific world picture will be to investigate the most primitive world picture, the naive world picture of the child.

Let us, therefore, try to place ourselves as best we can, in the child's mind and world of ideas. As soon as the child begins to think, he begins to form his world picture. For this purpose, he directs his attention toward the impressions which he receives through his sense organs. He tries to classify them, and in this endeavor he makes all kinds of discoveries, such as for instance, that there is a certain orderly interrelation between the inherently different impressions conveyed by the senses of sight, touch, and hearing. If you give the child a toy, let us say, a rattle, he will find that the tactile sensation is always accompanied by a corresponding visual sensation, and as he moves the rattle back and forth, he also perceives a certain regular auditory sensation.

While in this instance the different mutually independent sense worlds appear to be interlocking to a certain degree, on other occasions the child will make an observation which he will find to be no less remarkable—that certain impressions which are completely indistinguishable from one another and have their origin in a common sense world, may nevertheless be of a totally different character. Thus, for instance, the child may look at a round electric light and observe that it looks just like the full moon. The light sensation may be exactly the same. Yet, the child finds a great difference, for he can touch the lamp, but not the moon; he can pass his hand around the lamp, but not around the moon.

What, then, does the child think as he makes these discoveries? First of all, he wonders. This feeling of wonderment is the source and inexhaustible fountainhead of his desire for knowledge. It drives the child irresistibly on to solve the mystery, and if in his attempt he encounters a causal relationship, he will not tire of repeating the same experiment ten times, a hundred times, in order to taste the thrill of discovery over and over again. Thus, by a process of incessant labor from day to day, the child eventually develops his world picture, to the degree needed by him in practical life.

The more the child matures, and the more complete his world picture becomes, the less frequently he finds reason to wonder. And when he has grown up, and his world picture has solidified and taken on a certain form, he accepts this picture as a matter of course and ceases to wonder. Is this because the adult has fully fathomed the correlations and the necessity of the structure of his world picture? Nothing could be more erroneous than this idea. No! The reason why the adult no longer wonders is not because he has solved the riddle of life, but because he has grown accustomed to the laws governing his world picture. But the problem of why these particular laws hold, and no others, remains for him just as amazing and inexplicable as for the child. He who does not comprehend this situation misconstrues its profound significance, and he who has reached the stage where he no longer wonders about anything, merely demonstrates that he has lost the art of reflective reasoning.

Rightly viewed, the real marvel is that we encounter natural laws at all which are the same for men of all races and nations. This is a fact which is by no means a matter of course. And the subsequent marvel is that for the most part these laws have a scope which could not have been anticipated in advance.

Thus, the element of the wondrous in the structure of the world picture increases with the discovery of every new law. This holds true even of scientific research and inquiry in our own day, which continually produce something new. Just think of the mysteries of the cosmic rays, or the mysterious hormones, or the remarkable revelations of the electron microscope. To the research scientist, no less than to the child, it is always a gratifying experience and an added stimulus to encounter a new wonder, and he will labor industriously to solve the riddle by repeating the same experiments with his refined instruments just as the child does with his primitive rattle.

However, let us not leap too far ahead, but proceed in an orderly fashion. First, let us investigate in what respect the structure of the child's world differs from the sense world as originally given. The first fact to claim our attention is that sensations, the sole and exclusive constituents of the original world picture, have been driven appreciably into the background. The dominant elements of this world picture are not sensations, but the objects which produce them. The toy is a dominant element, and the tactile, visual, and auditory sensations are merely secondary consequences. But we would not do full justice to the state of affairs were we to say simply that this world picture is nothing but a synthesis of different sensory impressions achieved with the help of the unifying concept of *thing*. For, conversely, a single undifferentiated sense experience may correspond to several different objects. An example of this possibility is the previously mentioned case of an illuminated surface which produces in us a definite sensory impression, and yet is sometimes attributed to an electric light and at other times to the full moon. This is a case of a single undifferentiated sensation which corresponds to two different objects. The contrast, therefore, lies deeper, and can be characterized exhaustively only by introducing the concept of an objectively valid regularity. The sensations produced by objects are private, and vary from one individual to another. But the world picture, the world of objects, is the same for all human beings, and we may say that the transition from the sense world to the world picture amounts to a replacement of a disordered subjective manifold by a constant objective order, of chance by law, and of variable appearance by stable substance.

The world of objects, in contrast to the sense world, is therefore called the "real world." Yet, one must be careful when using the word *real*. It must be taken here in a qualified sense only. For this word has the connotation of something absolutely stable, permanent, immutable, whereas the objects of the child's world picture could not rightly be claimed to be immutable. The toy is not immutable, it may break or burn. The electric lamp can be smashed to smithereens. This precludes their being called real in the sense just mentioned.

This sounds both self-evident and trivial. But we must bear in mind that in the case of the scientific world picture, where as we have seen, the situation is quite analogous, this state of affairs was by no means found to be self-evident. For just as to the child the toy is the true reality, so for decades and centuries the atoms were taken by science to constitute the true reality in natural processes. The atoms were considered to be that which remains immutable when an object is smashed or burned, thus representing permanency in the midst of all change—until one day, to everybody's astonishment, it was found that even atoms could change. Therefore, whenever in the sequel we refer to the real world, we shall be using the word *real* primarily in a qualified, naive sense, adjusted to the particular character of the dominant world picture, and we must constantly bear in mind that a change in the world picture may go hand in hand, simultaneously, with that which people call real.

Every world picture is characterized by the real elements, of which it is composed. The real world of exact science, the scientific world picture, evolved from the real world of practical life. But even this world picture is not final, but changes all the time, step by step, with every advance of inquiry.

Such a stage of development is represented by that scientific world picture which today we are accustomed to call "classical." Its real elements, and hence its characteristic feature, were the chemical atoms. In our own day, scientific research, fructified by the theory of relativity and the quantum theory, stands at the threshold of a higher stage of development, ready to mould a new world picture for itself. The real elements of this coming world picture are no longer the chemical atoms, but electrons and protons, whose mutual interactions are governed by the velocity of light and by the elementary quantum of action. From today's point of view, therefore, we must regard the realism of the classical world picture as naive. But nobody can tell whether some day in the future the same words will not be used in referring to our modern world picture, too.

III

But what is the meaning of this constant shift in what we call real? It is not utterly unsatisfactory to all men who seek definite scientific insight?

The answer to this question must be, first of all, that our immediate concern is not whether or not the situation is satisfactory, but what its essentials are. But the pursuit of this question will lead to a discovery which we must regard as the greatest of all the wonders previously mentioned. First of all, it must be noted that the continual displacement of one world picture by another is dictated by no human whim or fad, but by an irresistible force. Such a change becomes inevitable whenever scientific inquiry hits upon a new fact in nature for which the currently accepted world picture cannot account. To cite a concrete example, such a fact is the velocity of light in empty space, and another is the part played by the elementary quantum of action in the regular occurrence of all atomic processes. These two facts, and many more, could not be incorporated in the classical world picture, and consequently, the classical world picture had to yield its place to a new world picture.

This in itself is enough to make one wonder. But the circumstance which calls for ever greater wonderment, because it is not self-evidently a matter of course by any means, is that the new world picture does not wipe out the old one, but permits it to stand in its entirety, and merely adds a special condition for it. This special condition involves a certain limitation, but because of this very fact it simplifies the world picture considerably. In fact, the laws of classical mechanics continue to hold satisfactorily for all the processes in which the velocity of light may be considered to be infinitely great, and the quantum of action to be infinitely small. In this way we are able to link up in a general manner mechanics with electrodynamics, to substitute energy for mass, and moreover, to reduce the building blocks of the universe from the ninety-two different atom types of the classical world picture to two—electrons and protons. Every material body consists of electrons and protons. The combination of a proton and an electron is either a neutron or a hydrogen atom, according as the electron becomes attached to the proton or circles about it. All the physical and chemical properties a body has may be deduced from the type of its structure.

The formerly accepted world picture is thus preserved, except for the fact that now it takes on the aspect of a special section of a still larger, still more comprehensive, and at the same time still more homogeneous picture. This happens in all cases within our experience. As the multitude of the natural phenomena observed in all fields unfolds in an ever richer and more variegated profusion, the scientific world picture, which is derived from them, assumes an always clearer and more definite form. The continuing changes in the world picture do not therefore signify an erratic oscillation in a zigzag line, but a progress, an improvement, a completion. In establishing this fact I have, in my opinion, indicated the basically most important accomplishment that scientific research can claim.

But what is the direction of this progress, and what is its ultimate goal? The direction, evidently, is the constant improvement of the world picture by reducing the real elements contained in it to a higher reality of a less naive character. The goal, on the other hand, is the creation of a world picture, with real elements which no longer require an improvement, and therefore represent the ultimate reality. A demonstrable attainment of this goal will—or can—never be ours. But in order to have at least a name for it, for the time being, we call the ultimate reality the real world, in the absolute, metaphysical sense of the word *real*. This is to be construed as expressing the fact that the real world—in other words, objective nature—stands behind everything explorable. In contrast to it, the scientific world picture gained by experience—the *phenomenological world*—remains always a mere approximation, a more or less well defined model. As there is a material object behind every sensation, so there is a metaphysical reality behind everything that human experience shows to be real. Many philosophers object to the word, *behind*. They say: "Since in exact science all concepts and all measures are reducible to sensations, in the last analysis the meaning of every scientific finding also refers only to the sense world, and it is inadmissible, or at least superfluous, to postulate the existence behind this world of a metaphysical world, totally inaccessible to direct scientific inquiry and examination." The only proper reply to this argument is, simply, that in the above sentence the word behind must not be interpreted in an external or spatial sense. Instead of "behind," we could just as well say, "in" or "within." Metaphysical reality does not stand spatially *behind* what is given in experience, but lies fully *within* it. "Nature is neither core nor shell—she is everything at once." The essential point is that the world of sensation is not the only world which may conceivably exist, but that there is still another world. To be sure, this other world is not directly accessible to us, but its existence is indicated, time and again, with compelling clarity, not only by practical life, but also by the labors of science. For the great marvel of the scientific world picture, becoming progressively more complete and perfect, necessarily impels the investigator to seek its ultimate form. And since one must assume the existence of that which one seeks, the scientist's assumption of the actual existence of a real world, in the absolute sense of the word, eventually grows into a firm conviction which nothing can shake any more. This firm belief in the absolute real in nature is what constitutes for him the given, self-evident premise of his work; it fortifies repeatedly his hope of eventually groping his way still a little nearer to the essence of objective nature, and of thereby gaining further clues to her secrets.

Since the real world, in the absolute sense of the word, is independent of individual personalities, and in fact of all human intelligence, every discovery made by any individual acquires a completely universal significance. This gives the inquirer, wrestling with his problem in quiet seclusion, the assurance that every discovery will win the unhesitating recognition of all experts throughout the entire world, and in this feeling of the importance of this work lies his happiness. It compensates him fully for many a sacrifice which he must make in his daily life.

The sublime nature of such a goal must, necessarily, dwarf into insignificance any doubt engendered by the difficulties encountered while shaping the scientific world picture. It is particularly important to emphasize this in our own day, for nowadays such difficulties are sometimes regarded as serious impediments to the salutary progress of scientific work. It is an odd fact that experimental difficulties are so regarded to a lesser degree than theoretical ones. The circumstance that with the increasing demands on the accuracy of measurements the instruments, too, become more intricate, is understood and accepted as a matter of course. But the fact that, in the endeavor to improve continually the expansion of systematic interrelations, it is necessary to use definitions and concepts which diverge more and more from traditional forms and intuitive notions, is sometimes cited as a reproach against theoretical research, and is even viewed as indicating that theoretical research is entirely on the wrong track.

Nothing could be more shortsighted than such a view. For if we stop to think that the improvement of the world picture goes hand in hand with an approach to the metaphysically real world, the expectation that the definitions and concepts of the objectively real world picture will not diverge too much from the framework created by the classical world picture amounts basically to a demand that the metaphysically real world be completely intelligible in terms of ideas derived from the former naive world picture. This is a demand that can be never fulfilled. We simply cannot expect to recognize and discern the finer structure of something, so long as we flatly refuse to view it otherwise than with the naked eye. Yet, in this respect there is no reason for fear. The development of the scientific world picture is a matter of absolute necessity. The experiences gained with the refined instruments of measurement demand inexorably that certain firmly rooted intuitive notions be abandoned and replaced by new, more abstract conceptual structures, for which the appropriate intuitions are still to be found and developed. Thus, they are the landmarks to guide theoretical research on its road from the naive concept of reality to the metaphysical real.

But significant as the achievements may be, and near as the desired goal may seem, there always remains a gaping chasm, unbridgeable from the point of view of exact science, between the real world of phenomenology and the real world of metaphysics. This chasm is the source of a constant tension, which can never be balanced, and which is the inexhaustible source of the insatiable thirst for knowledge within the true research scientist. But at the same time, we catch here a glimpse of the boundaries which exact science is unable to cross. May its results be ever so deep and far-reaching, it can never succeed in taking the last step which would take it into the realm of metaphysics. The fact that although we feel inevitably compelled to postulate the existence of a real world, in the absolute sense, we can never fully comprehend its nature, constitutes the irrational element which exact science can never shake off, and the proud name "exact science" must not be permitted to cause anybody to underestimate the significance of this element of irrationality. On the other hand, the very fact that science sets its own limits on the basis of scientific knowledge itself, appears well suited to strengthen everybody's confidence in the reliability of that knowledge, knowledge obtained on the basis of incontestable presupposition and with the help of rigorous experimental and theoretical methods.

If, now, we cast our glance from the viewpoint now established back on the starting point of our considerations, and on the entire train of thoughts pursued, the results gained will become even clearer. We began our deliberations with a definite disillusionment. We sought a universal foundation on which to erect the edifice of exact science, a foundation of indisputable firmness and security—and we failed to find it. Now in the light of the insights gained, we recognize that our quest was doomed to failure even before it started. For, basically considered, our attempt was based on the idea of starting out on our scientific exploration from something irrevocably real, whereas we have now come to understand that such ultimate reality is of a metaphysical character and can never be completely known. This is the intrinsic reason that doomed to failure every previous attempt to erect the edifice of exact science on a universal foundation, valid a priori. We had to be satisfied, instead, with a starting point which was of inviolable solidity and yet of an extremely limited significance, since it was based solely on individual data of experience. It is at this modest point that scientific research enters with its exact methods, and it works its way step by step from the specific to the always more general. To this end, it must set and continually keep its sights on the objective reality which it seeks, and in this sense exact science can never dispense with reality in the metaphysical sense of the term. But the real world of metaphysics is not the starting point, but the goal of all scientific endeavor, a beacon winking and showing the way from an inaccessibly remote distance.

The assurance that every new discovery, and every new fact of knowledge gained from it, will bring us nearer to the goal, must compensate us for the numerous, and certainly not negligible, drawbacks which are necessarily created by the continual abatement of the intuitive character and ease of application of the world picture. In fact, the present scientific world picture, as against the original naive world picture, shows an odd, almost alien aspect. The immediately experienced sense impressions, the primordial sources of scientific activity, have dropped totally out of the world picture, in which sight, hearing, and touch no longer play a part. A glance into a modern scientific laboratory shows that the functions of these senses have been taken over by a collection of extremely complex, intricate, and specialized apparatus, contrived and constructed for handling problems which can be formulated only with the aid of abstract concepts, mathematical and geometric symbols, and which often are beyond the layman's power of understanding. One might feel completely at sea trying to puzzle out the meaning of exact science, and exact science has even been accused on this account of having lost its firm footing with the loss of its original intuitive character. But he who persists in this opinion, despite the reasons cited, is beyond help, and will be as unable to make any essential contribution to the progress of exact science as an experimenter who insists, as a matter of principle, on working always with primitive instruments only. For exact science demands more than a gift of intuition and willingness to work hard. It demands also very involved, painstaking, tedious attention to details, for which many scientists must often pool their efforts in order to prepare their branch of science for the next step on the ladder of gradual progress. To be sure, when the pioneer in science sends forth the groping feelers of his thoughts, he must have a vivid intuitive imagination, for new ideas are not generated by deduction, but by an artistically creative imagination. Nevertheless, the worth of a new idea is invariably determined, not by the degree of its intuitiveness—which, incidentally, is to a major extent a matter of experience and habit—but by the scope and accuracy of the individual laws to the discovery of which it eventually leads.

Of course, every step forward means also that the difficulty of the task increases, the demands on the analyst grow more exacting, and the need for an expedient division of labor becomes always more urgently imperative. In particular, the division of science into experimental and theoretical was completed about a century ago. Experimenters are the shock troops of science. They perform the decisive experiments, carry out the all-important work of measurement. An experiment is a question which science poses to nature, and a measurement is the recording of nature's answer. But before an experiment can be performed, it must be planned—the question to nature must be formulated before being posed. Before the result of a measurement can be used, it must be interpreted—nature's answer must be understood properly. These two tasks are those of the theorist, who finds himself always more and more dependent on the tools of abstract mathematics. Of course, this does not mean that the experimenter does not also engage in theoretical deliberations. The foremost classical example of a major achievement produced by such a division of labor is the creation of spectrum analysis by the joint efforts of Robert Bunsen, the experimenter, and Gustav Kirchoff, the theorist. Since then, spectrum analysis has been continually developing and bearing ever richer fruit.

Whenever an experimental finding contradicts the accepted theory, another step on the ladder of progress is thereby announced, for the contradiction signifies that the accepted theory must be overhauled and improved. But the question as to just where and how to change it entails serious difficulties. For the more tried an existing theory is, the more sensitive it is, and the stronger resistance it puts up to every attempt to alter it. In this respect, it behaves like a highly complex, widely ramified organism, whose individual component parts are mutually interdependent and are so closely interlinked that a reaction to any stimulus at any one point is also manifested automatically at quite different and, seemingly, very remote places. This gives rise to new questions, which can be investigated experimentally, and thus it may lead to consequences, the bearing and importance of which no one could suspect at the outset. This is how the theory of relativity was born, and this is the story behind the genesis of the quantum theory. In our own days, the constant growth and advancement of the youngest branch of natural science, nuclear physics, brought about and implemented by a reciprocal supplementation of experiment and theory, is another typical example of such fruitful collaboration.

IV

But why all this enormous labor, demanding the best efforts of countless soldiers of science during their entire lives? Is the ultimate result—which, as we have seen, in its individual details always drifts away from the immediately given facts of life—truly worth this costly effort?

These questions would indeed be justified if the meaning of exact science were limited to a certain gratification of man's instinctive yearning for knowledge and insight. But its significance goes considerably deeper. The roots of exact science feed in the soil of human life. But its link to it is twofold. For it not only has its source in experience, but also has a retroactive effect on human life, both material and spiritual, and the more freely it can unfold itself, the stronger and more fruitful is this effect. This manifests itself in a very peculiar manner. First, as we have found, when science works on the world picture of its own making, its quest of metaphysical reality causes it to drift always farther and farther away from the immediate facts and interests of life, since it always takes to less intuitive and more solitary trails. But these trails, and only these, are the very paths leading toward a discernment of new laws of interrelations, which would be inaccessible in any other way, and which can then be made relevant for human experience and thus made to serve human needs.

This fact can be observed in countless individual instances. Here, too, a far-reaching division of labor has proved its worth excellently. The first step, the moulding of the world picture from its beginnings in ordinary experience, is the task of pure science. The second step, the practical utilization of the scientific world picture, is the task of technology. Both these tasks are equally important, and since either of them demands a man's full energy, if an individual scientist wants to make progress in his work, he must concentrate all his energy on one single task and for the time being forget completely other problems and interests. For this reason, never reproach the scholar too harshly for his other-worldliness and his indifference to important problems of human society. Without such a one-sided attitude, Heinrich Hertz could never have discovered radio waves, or Robert Koch the tubercle bacillus. These gifts of pure scientific research to practical life have their counterparts in the manifold stimuli and intelligent assistance which science receives from technology, a fact that is becoming progressively more manifest in our day and whose importance cannot be assessed too highly.

I feel I must discuss here a little more closely, by way of an example, a very recent and very impressive case of the often quite unsuspected close interrelation of science and technology. For a great number of years, only men of pure science were interested in the distinctive facts of atomic transformations. To be sure, the magnitude of the energies thus released did attract attention, yet since atoms were so infinitesimally small, no serious thought was given to the possibility that one day they might acquire practical significance, too. Today, due to new findings in the field of artificial radioactivity, this question has taken an astonishing turn. The investigations of Otto Hahn and his collaborators have established the fact that a uranium atom bombarded by a neutron splits into several parts. Two or three neutrons are liberated, and each of them continues on its own path and may, in its turn, collide with a uranium atom and split it. Thus the effects may multiply; and it may happen that as a consequence of the increasing bombardment of uranium atoms by the liberated neutrons the energy thus released will swell like an avalanche within a very short time. To visualize this, think of the well-known example of chain letters. With the number of available atoms, this chain reaction may reach quite enormous, hardly conceivable proportions. Of course, an indispensable prerequisite for this effect is that the free neutrons, prior to their hitting uranium nuclei, are not captured by other atoms and either permanently absorbed by the latter or deflected away from uranium nuclei.

A specific computation has shown that the amount of energy released in this manner in a cubic meter (35.314 cubic feet) of powdered uranium oxide within one one-hundredth of a second is sufficient to lift a weight of one billion metric tons to a height of almost 17 miles. This amount of energy could replace the output of all the big power plants of the world combined for many years.

Up to quite recently, a technical utilization of the energy latent in the nuclei of atoms might have appeared as a utopian dream. But it was made a reality about 1942, by the impressive collaboration of British and American scientists with American industry, backed by huge government subsidies. At the present moment, several uranium piles are operating in America, and the heat continually produced by them is sufficient to raise the temperature of the Victoria River in the state of Washington by 1 degree Centigrade. So far as the reports disclose, these vast amounts of energy are still unused. Right now, the problem is to get rid of them in a harmless way. But these same piles furnish also the raw materials for the atomic bombs, in which vast amounts of the nuclear energy of the atom are liberated within a fraction of a second, producing explosions beside which the devastation caused by all chemical explosives fades into insignificance. No words can be strong enough to overemphasize the danger of self-extermination which threatens the entire human race, should a future war bring about the use of a large number of such bombs. Human imagination is incapable of conceiving the possible consequences. A particularly eloquent and forceful plea for peace is the memory of the 80,000 dead of Hiroshima and the 40,000 dead of Nagasaki, a plea addressed to all nations, and especially to their responsible leaders.

In view of these facts, perhaps many who have lost the art of wondering may feel disposed to learn it anew. And in fact, compared with immeasurably rich, ever young nature, advanced as man may be in scientific knowledge and insight, he must forever remain the wondering child and must constantly be prepared for new surprises.

Thus we see ourselves governed all through life by a higher power, whose nature we shall never be able to define from the viewpoint of exact science. Yet, no one who thinks can ignore it. A thinking human being, who has not only scientific but also metaphysical interests, must choose one of two possible attitudes: either fear and hostile resistance or reverence and trusting devotion. If we reflect on all the unspeakable suffering and incessant destruction of life and property which have plagued mankind since time immemorial, we may be tempted to agree with the pessimistic philosophers who consider life worthless and deny the possibility of permanent progress, of a betterment of mankind, and who profess instead that it is the fate of every human civilization to turn blindly against itself as soon as it reaches a certain peak, and to destroy itself without sense or purpose.

May exact science be cited as an evidence of such a far-reaching view? The answer must be "No," if for no other reason than because science is not qualified to decide the question. From the scientific point of view, one might just as well, and perhaps with even more justification, endorse the opposite opinion. It would require merely an extension of the range of observation, a thinking not in terms of centuries but of many millennia. Or is there anybody who would seriously deny that during the past one hundred thousand years *Homo sapiens* has made progress and has improved himself? Why should this progress not continue further—if not in a straight line, then at least in waves?

Of course, such considerations, such a long range view, are no help to the individual. They cannot bring him succor in his hour of need or cure his pain. The individual has no alternative but to fight bravely in the battle of life, and to bow in silent surrender to the will of a higher power which rules over him. For no man is born with a legal claim to happiness, success, and prosperity in life. We must therefore accept every favorable decision of providence, each single hour of happiness, as an unearned gift, one that imposes an obligation. The only thing that we may claim for our own with absolute assurance, the greatest good that no power in the world can take from us, and one that can give us more permanent happiness than anything else, is integrity of soul, which manifests itself in a conscientious performance of one's duty. And he whom good fortune has permitted to cooperate in the erection of the edifice of exact science will find his satisfaction and inner happiness, with our great German poet, in the knowledge that he has explored the explorable and quietly venerates the inexplorable.

This chapter is taken from the forthcoming book Scientific autobiography and other papers *by the late Max Planck, to be published by the Philosophical Library on October 17.*