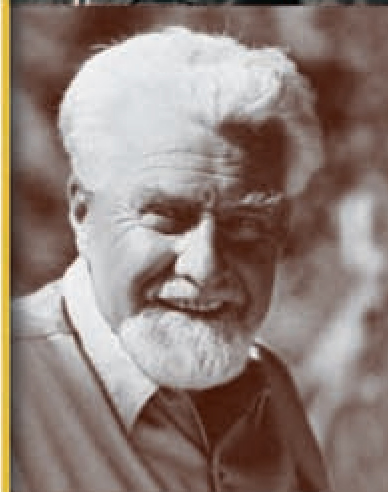




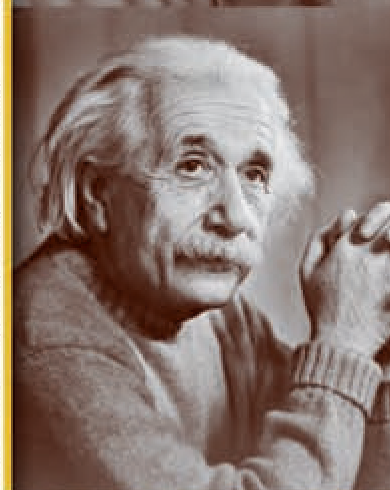



From Galileo *to* Gell-Mann

THE WONDER THAT INSPIRED THE GREATEST SCIENTISTS OF ALL TIME

In Their Own Words

MARCO BERSANELLI & MARIO GARGANTINI



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Marco Bersanelli & Mario Gargantini

Translated by John Bowden

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It is prime evidence of an amazement with which the attitude of the true researcher is charged; the marvel of the presence attracts me; it so to speak sparks off the research in me.

Luigi Giussani

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Preface

On October 4, 1957, the Feast of St. Francis of Assisi, for the first time in the history of humankind the then Soviet Union placed an artificial satellite into orbit, the famous Sputnik. This event also had an enormous importance from a political perspective, because it demonstrated the capacity that the Soviet Union had achieved with rockets that were capable of launching not only satellites but also nuclear warheads, with all the implications that this had for the so-called Cold War and the security of the West. Moreover, it had a fundamental long-term importance from a technological point of view, because of the great stimulus it provided for space research not only in the Soviet Union but above all in the United States. In fact, a few years later, President Kennedy, in a famous speech, promised the full support of the U.S. government for the development of the necessary technology to reach the moon before the end of that decade.

In a far less transcendental way, the same event had a direct influence on my life. October 4 was also my birthday. I was fifteen, an age at which I was still very flexible and ready to wonder at and absorb all that the world could offer. It was my penultimate year at school, and I was planning to follow in my father's footsteps and become a civil engineer, and later go on to work in his construction firm. However, the marvel of Sputnik's launching made me dream, and I began to think that "when I grew up" I would like to work in space research, a field that was opening up at that very moment. When I left school the next year, I enrolled in physics instead of engineering, and my road to space research had begun.

This episode in my life serves simply to illustrate, from a very personal point of view, how amazement and wonder at the world that surrounds us and at all creation have a determining influence on our choices and on our future. In my case, this amazement was also accompanied by the faith that supported me and shaped not only my search for answers to the problems of the material world but above all my research into why things are as they are. Amazement and wonder move each one of us from within to seek an equilibrium between the pure reason of the world of physics and the philosophical investigation of the meaning of things and being.

I am fortunate enough to work in an area of science, astronomy, that I believe fascinates everyone since it seeks to give answers to some questions that human beings have asked since time immemorial. Where do we come from? What was the origin of our world and our universe? Are there other intelligent beings in this universe? These are questions that not only relate to pure scientific research but also have profound links with other forms of knowledge: we can also raise the same questions and find answers in the philosophical or theological sphere.

In past centuries the possibility of answering all these questions with completely different methodologies and often with contrasting results was the source of controversies and misunderstandings, giving rise to direct conflicts between the scientific view and religious doctrine, to the point of creating over the years a barrier between the two.

Today science and theology are more aware of the specific nature of their methods, and take care to avoid "incursions" into what is clearly the field of the other. However, the mistakes made in the distant past continue to have a negative influence on many of those who dedicate themselves to scientific research, nurturing the conviction that to make progress it is necessary to refute completely, or even to ridicule, any notion that comes from faith or philosophical research. It should be added that often our scientists show a good deal of intellectual arrogance and, believing that they have "understood" how the universe was made and how it evolved, they think that they can "demonstrate" that there is no need for God to give life to our universe and ourselves. Moreover, some of our colleagues even think that we are in a position to create other universes for ourselves. In other words, first we do everything possible to deny the existence or the need for God and then we try to invent a "better" god of our own making to put in his place.

I personally believe that there is no necessary conflict between religious experience and science. Thus, both scientific research and the quest for God are profound expressions of our reality as human beings. The bond between science and religion is the quest for the "truth." However, the methods are very different: in scientific research the "truth" is by definition not absolute, but the result of our knowledge at a particular time. This is not the "Truth" with a capital T, but a paradigm that is continually evolving. Major scientific discoveries have often led to the substitution of one paradigm with another, and in this way we come nearer to the "truth." I am not the right person to speak of the concept of truth from a philosophical or theological perspective: numerous famous philosophers have written many profound books on this subject. I simply think that the dialogue that is intensifying between theology, philosophy, and science can first of all lead to an understanding of the objectives and the limitations of each of these disciplines and then prepare the road so that, through confrontation of ideas and constructive dialogue, each in its own specific field will contribute to the quest for that Truth which is God.

In this book we will read accounts of the experiences of numerous researchers in different disciplines; the guiding thread is one that runs from wonder to observation to discovery and takes us back to our wonder faced with the beauty of creation. For those who, like myself, work in astronomy, it is natural to think of the beautiful images that have been obtained with the Hubble Space Telescope: these are images that not only fill the "professionals" with wonder but, through their visual and aesthetic impact, succeed in attracting the attention of the nonspecialist public and involving them in the adventure of research not only as spectators but, at least in part, as protagonists.

As Aleksandr Solzhenitsyn said in one of his addresses, I believe in God because there is beauty.

And what is more beautiful than creation?

Duccio Macchetto

Introduction

Science occupies a central position in the interests and preoccupations of contemporary men and women. In knowledge the markers are being moved further and further forward in a headlong course that seems unstoppable. The applications are extending toward fields that at one time were unthinkable, sometimes coming to threaten natural balances and the very integrity of the person.

A sense of fear, or at least of great concern, is spreading in the current climate, while critical voices are multiplying that call for caution and greater control. Nevertheless, in relevant sectors of public opinion and also in the minds of many researchers, the fixed image continues to be that of science as a neutral activity in which the human being seems to have a secondary or even insignificant part—so much so that questions about the motivation for research seem quite out of place. The framework of scientific knowledge still seems to be a self-defined structure, not subject to anything above or outside itself and therefore free of conditions and not bound by responsibility and judgment.

This is an image that in part corresponds to the way in which science has developed historically in these three centuries, marked by a claim to self-sufficiency in respect of the human subject who is, on the other hand, its architect and user. However, if we try to catch the experience of those who have lived and still live the adventure of research in the first person, beginning with the greatest protagonists, we realize how much the act of scientific knowledge is inseparable from human beings and their interests, in such a way that in the activity of research the whole person is brought into play; here human relations, tacit motivations, social responsibility, desire, the unforeseen, drama, despair, passion, error, and faith are all interwoven.

The anthology contained in this book brings together fragments of thought and testimonies with the aim of offering a "live" cross-section of the dynamics of research. For this reason we have wanted to allow protagonists rather than spectators or critics to have their say: the anthology is made up of passages from scientists from all times and all disciplines—but only scientists. As we shall see, their positions and their judgments on the value and meaning of research are very diverse—and we are far from being able to claim that we have presented them completely here. But in the diversity of such positions one may find a surprising passion and a tension with the truth that is perhaps unknown to many people.

The experience of research takes place as a struggle with the mystery of reality, according to the partial but original perspective offered by the scientific method. In various ways, scientists are moved by the hope of grasping the order and direction of the natural world, taking account of it in the cosmic context in which we live, and catching sight of the possible unity of the universe behind the multiplicity of forms. For the scientist in action, the basic questions relate to this struggle; they are implicitly but potentially at work in the very movement of knowledge, in research into the twists and turns and the matter of the material world. In this sense, scientific knowledge, too, is in its way a manifestation of that incurable tendency of the human being to ask why things are as they are, never satisfied with partial answers. That does not mean that the relationship between scientific knowledge and religious sense involves building an improbable bridge between two distant banks; rather, scientific research proves to have its seed and its profound roots in the human need for satisfaction and meaning.

The subdivisions in the chapters arrange the material according to some key words (wonder, observation, experiment, discovery, certainty, sign, purpose). It has not been easy to make identifications, nor have we taken them for granted, and often we have been tempted to modify the scheme. The passages are introduced and commented on according to an approach that sets out to document the event of scientific knowledge as an amazing encounter between a subject and an object, between the human being and the cosmos—an encounter in which reason shows itself in its nature of openness to the world, its demand for exhaustive meaning.

At the origin of the phenomenon of scientific knowledge, we find wonder and the contemplation of reality, as we find it created in front of us and not in accordance with the affirmation of our sensibilities or a preconceived image.

Therefore, to say that in the mind of the scientist there is something like a child-like spirit is not a rhetorical phrase but indicates a distinctive feature of the attitude required to understand reality: to know how to look, to allow oneself to be amazed by what is there. This disposition not only accompanies the beginning of research and then gives way to reasoning and deduction: every step in the investigation—from observation to experiment, from discovery to verification—is a "beginning" and is supported by the attraction of what exists.

Priority has been given to texts that bring out the factors of human experience involved in the practice of scientific work and the feeling of reality that develops in the attempt to look at and interrogate nature. However, many great scientists have written little or nothing about their human and scientific experience and have only published the results of their researches. Inevitably we have found more space in this work for persons who in one way or another have had the concern and the interest to reflect on their own cognitive experience, or at any rate have wanted to and been able to relate something of what has happened to them. This same focus on experience also means that some topics, the object of both scientific and philosophical debate, are only touched on here and not dealt with adequately; however, for them the interested reader will be able to follow first suggestions from the numerous sources indicated in the notes.

Sometimes the choice of the position of a passage in a given chapter or section may appear somewhat arbitrary, especially when problems are raised on the borders of various aspects. We have tried to follow the criteria of expository clarity and continuity, but this has not always been possible. Each chapter is subdivided into sections, the title of which combines a second key word with the main topic (as for example "Discovery and the unforeseen" or "Sign and design"); we have done this in an attempt to help to identify or construct links between kindred subjects distributed over different chapters. A brief biography of all the scientists is presented in the appendix—this makes it possible to put the person and the work in a historical and scientific context.

This book is not addressed solely to "specialists" in scientific matters. Therefore as an aid to reading there are numerous notes and a glossary with a summary explanation of recurring technical terms. However, some passages—in fact, a very small minority—could be difficult to understand because of a rather higher technical level. We have decided to keep them because it is clear that the liveliness of their existential content can be grasped with a little patience if readers accept that they will not follow all the details of the debate.

The book is the result of meetings, lectures, discussions, and public and informal conferences that have involved the members of Euresis[1]—for the most part scientists, but not just scientists—whose company has been a source of energy and imagination in the course of the work. The book came into being as an attempt to bring some order to readings, comments, and material collected in various circumstances. It is impossible to compile an exhaustive list of those whom we would like to thank, and who have contributed in a very important way to this work, directly or indirectly. We are grateful to Stefania Ragusa for her patient and precise editorial work and to Maria Elisa Bergamaschini for a critical rereading of the text. Elena Chierici and Nicola Sabatini have contributed to the translations and the discovery of some sources. Finally, we are grateful for advice or suggestions from Vittorio Banfi, Marco Barbetta, Tommaso Bellini, Davide Caironi, Benedetta Cappellini, Giovanni Comelli, Constantino Esposito, Giorgio Guidi, Raffaella Manara, Gabriele Mangiarotti, Lorenzo Mazzoni, Francesco Prestipino, Davide Prosperi, Lucio Rossi, Elio Sindoni, Cristiana Speciani, and Giuseppe Tanzenella-Nitti.

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From Galileo to Gell-Mann

Wonder 1

No less worthy of exaltation and amazement is the setting for human life: this vast, mysterious, magnificent world, this universe of a thousand forces, a thousand laws, a thousand beauties, a thousand depths. Have I studied sufficiently, explored, admired the space within which life is lived? What an unforgivable distraction, what blameworthy superficiality! **PAUL VI**

Those who have reached the stage of no longer being able to marvel at anything simply show that they have lost the art of reasoning and reflection. **MAX PLANCK**

FROM TIME TO TIME, particular words enter scientific jargon that reveal the way in which scientists work on the natural world that they try to get to know. Thus, in the pages of a review of particle physics or in the thick of the discussion at a conference on molecular biology or astrophysics, it is easy to run into the word "evidence." Scientific research continuously feeds on and thrives on experimental evidence: there are the facts, the characteristics, the information that derive from a laboratory investigation or a program of observations carried out perhaps with extremely sophisticated instruments and methods of analysis. In the end, a step forward is taken only when evidence emerges from all this: at one point, however infinitesimal, reality shows its face, its mode of being. And this mode of being is persuasive;

it is a point at which it is no longer necessary to say more, but simply to recognize the facts. The term "evidence" brings out a simple but profound truth, yet one that is important: scientists can undertake their research only because the natural phenomena in some way put themselves in front of them as "facts," as the inexorable emergence of their being there and their mode of relating themselves to the rest of reality.

The starting point for the cognitive adventure of science is not therefore something that we invent for ourselves, but reality, which comes to us as evidence. It is a reality that presents itself with some characteristics, apparently obvious but not always well received in the dominant cultural terms of reference, whether in popularization or in the media.

The world that the scientist observes and investigates first of all exists: it is not an illusion nor a daydream. Those who have faced the challenge of research know very well that nature does not obey their imagination. Scientists are well aware of this when answers are slow in coming from their experiments or when after a great deal of toil they have an intuition of the perspective that allows them finally to see a glimmer of a relationship that binds the factors of a problem together.

Noting the presence of things is the first and fundamental action of the human being who knows. It is from this strange passivity that curiosity, questions, the desire for research grow. Perhaps for this reason, at the heart of all great scientists there is something that, as in a child, keeps their eyes wide open and focused on reality. The existence of things is the object of recognition but not of demonstration. And perhaps this can stimulate our mentality, still led to give value to only what can be demonstrated, as if the only credible knowledge were that of a mathematical kind. However, even a great logician such as Wittgenstein could not avoid recognizing that "an experience is such that when I prove it to myself I marvel at the existence of the world. And here I am inclined to use phrases such as 'how extraordinary it is that something exists' or 'how extraordinary it is that the world exists.'" This wonder at existence is the condition for an authentic encounter with things and opens up the possibility of knowledge. If in fact we ask what moves researchers to their research, we have to admit that their reason is set in motion by an attraction that reality exercises on them. However, the origin of this attraction is not directly the fact that they can "measure," "divide" things, but the simple and giddy fact that reality is there. It is wonder that things are there. This is a wonder that does not stop at an aesthetic sentiment, is not reduced to a momentary curiosity, but is the beginning of a process, kindling the desire to enter into relationship with the world, to get to know it. Wonder accompanies every step; every step of research is in fact a beginning.

Human reason is first of all provoked, moved by the fact that reality is there. What reason first acknowledges is the pure presence of things ("Look at the stars!"). But the capacity for wonder also becomes fruitful from a strictly scientific point of view. First of all, it makes scientists more attentive because they are wholly open to the data of reality, intent on interacting with them, and allow themselves to be provoked and therefore to respond, bringing all their own rational capacity to bear. It is fundamental for scientists to appreciate the beauty of the nature that they are studying, to be attracted by the sense of order and the regularity that they perceive in it. Scientists are thus led to collect all the data and are therefore put in a position to be able to grasp reality in all its expressions, in all its facets, including the quantitative aspects that help them to decipher the phenomena and go back rationally to the causes.

Quantitative curiosity ("How many stars are there?") is entirely based on this perception of the real as given and on the amazement that derives from it. The quantitative question that characterizes the scientific method arises as a particular expressive mode of the original amazement. The "measurable" aspect is a partial character, selected from the real: clearly there is much more to the world than being able to divide it and measure it. Scientific research has its specific character in the fact that it proceeds by asking "quantitative" questions that are addressed to the measurable components of reality. However, what moves research and gives energy to those who devote themselves to it does not arise from a logical deductive capacity but from an affective energy: that which makes a human being "a lover of being," desiring to know reality and interested in its possible meaning.

Wonder and Reality: New Territory Spread Out before My Eyes

The repercussions for the existence of natural reality imply the awareness that nature is there before us, precedes us. Physical reality presents itself as a "datum." This is an expressive term of scientific language: researchers live immersed in data, they collect them, elaborate them, confront them, interpret them, make links between them. . . . In any case we cannot ignore the fact that there is a reality that comes as a "given": the given of the problem or the experiment is something that is offered, something one encounters. Heisenberg even uses the word "gift" to express the nature of the objective fact that emerges to his awareness.

Werner Heisenberg[1]

The last few weeks have been very exciting for me. Perhaps an analogy is the best way of describing my experiment: that of the attempt to attain the summit of atomic theory which is still unknown, an attempt which has required great efforts of me over the last five years. And now the summit is there in front of me; the whole area of internal relations in atomic theory is unexpectedly and clearly spread out before my eyes. What these internal relations show in all their mathematic abstraction, an incredible degree of simplicity, is a gift that we can only accept with humility. Not even Plato could have believed that it would be so beautiful. In fact these relations cannot have been invented: they have existed since the creation of the world.

Here Heisenberg emphasizes his amazement at the undeniable fact that atomic theory is woven together from relatively simple internal relations. This is not expected. In reality it is an absolutely surprising fact that reality allows itself to be known, that the scientific enterprise in all its complexity is possible. This requires that not only is there an order in reality, but also that human beings (human reason) are in a position to establish a relationship with this order in some way. Trust in such an accessible order is essential for embarking on the adventure of knowledge.

On the other hand, physical reality also appears unattainable in its ultimate consistency (if one thinks of the initial moment of the big bang or of the elementary particles). One gets the impression that the ultimate level of reality is always beyond what reason can define and understand. It is always a terra incognita, a level that cannot be attained. Reality is at the same time both accessible and inaccessible. In this sense, scientific research sheds light on the nature of reality as "mystery": it exists, it establishes a relationship with it, but ultimately escapes the complete understanding of reason. It is as if all our knowledge or achievements related inexorably to an ultimate and hidden object. "It is an endless struggle with the mystery."

This is the enthralling condition that imposes itself on research, which is at the same time humbling in the sense that it makes us humble before the mystery of reality, the ultimate nature of which is always superfluous to all our cognitive and creative capacities. Far from being frustrating, it is more of an "adventurous" condition.

The sense of adventure in scientific research has rarely been described so effectively and concisely as in the brief comment by Richard Feynman that follows. The perception of the ultimately unfathomable nature of the natural world is a fascinating starting point.

Richard Feynman[2]

The same thrill, the same awe and mystery, come again and again when we look at any problem deeply enough. With more knowledge comes deeper, more wonderful mystery, luring one on to penetrate deeper still. Never concerned that the answer may prove disappointing, but with pleasure and confidence we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries—certainly a grand adventure!

The capacity for wonder, for marveling at nature as something "given" and "mysterious," is identified by Einstein with "the" fundamental characteristic of the scientist. It is a characteristic that scientists share with artists, who are also caught up in the quest for truth and expressivity.

Albert Einstein[3]

The most beautiful and deepest experience a man can have is the sense of the mysterious. It is the underlying principle of religion as well as all serious endeavor in art and science. He who never had this experience seems to me, if not dead, then at least blind. . . . To sense that behind anything that can be experienced there is something that our mind cannot grasp and whose beauty and sublimity reaches us only indirectly and as a feeble reflection, this is religiousness. In this sense I am religious. To me it suffices to wonder at these secrets and to attempt humbly to grasp with my mind a mere image of the lofty structure of all that is there.

The wonder is not in fact circumscribed and delimited in advance of knowledge, as is commonly thought. Indeed the very acquisition of knowledge is the cause of another wonder. It is as if the advance in our capacity to describe nature scientifically inexorably increases our perception of the inexhaustible character of reality.

Carlo Rubbia[4]

I have already said this many times, but it gives me great pleasure to repeat it. When we look at a particular physical phenomenon, for example a starry night, we feel deeply moved; we feel within ourselves a message which comes from nature, which transcends it and dominates it. The specialist, the researcher who sees into things, feels much more strongly, much more intensely, this same sensation of amazement, of wonder, at what each of us regards as a natural phenomenon. The beauty of nature, seen from within and in its most essential terms, is even more perfect than what appears externally: the inside of things is even more beautiful than the outside, so that I feel neither alarm nor fear. I feel curiosity and am honored to be able to see these things, fortunate, because nature is in fact a spectacle that is never exhausted.

A great philosopher such as Immanuel Kant, when putting himself in the shoes of the scientist grappling with cosmology, experienced the amazement that grows as scientific enquiry broadens the confines of the known universe. He put it like this: "With what astonishment will one be enchanted if one considers the infinite amount of worlds and systems which fill the totality of the Milky Way; but how this astonishment increases when one realizes that all these immeasurable star-orders again form the unit of a number whose end we do not know and which perhaps just as the former is conceivably great and yet again is only the unit of a new number system. We see the first members of a progressive relation of worlds and systems, and the first part of this infinite progression makes already known what one must conjecture about the whole. There is no end here but an abyss of a true immeasurability in which all ability of human concepts sinks. . . ."[5]

But the perception of the inexhaustibility of reality did not have to wait for Newtonian science to show itself. In ancient Greece the awareness of the giddy vastness and variety of the world was alive and grew to the degree that it is, or can be, noted by the researchers of the third millennium.

Archimedes[6]

There are some, king Gelon, who think that the number of the sand is infinite in multitude; and I mean by the sand not only that which exists about Syracuse and the rest of Sicily but also that which is found in every region whether inhabited or uninhabited. Again there are some who, without regarding it as infinite, yet think that no number has been named which is great enough to exceed its multitude.

Maria Mitchell[7]

These immense spaces of creation cannot be spanned by our finite powers; these great cycles of time cannot be lived even by the life of a race. And yet, small as is our whole system compared with the infinitude of creation, brief as is our life compared with cycles of time, we are so tethered to all by the beautiful dependencies of law, that not only the sparrow's fall is felt to the outermost bound, but the vibrations set in motion by the words that we utter reach through all space and the tremor is felt through all time.

Wonder and Beauty: The Unmistakable Fascination of the Thoroughbred

We have asserted that what attract reason and set research in motion are ultimately the consequences of the sheer presence of things and the attraction that they exercise. This initial attractiveness grows with the first steps of knowledge. The perception of a beauty, hidden but perceptible, always feeds the fruitful relationship with reality; scientific knowledge is no exception. It is difficult to find great scientists who have not explicitly described their decisive experience of the perception of beauty as the hidden order of the laws of nature that they desire to master.

Marie Curie[8]

I belong in the ranks of those who have cultivated the beauty that is the distinctive feature of scientific research. A scientist in the laboratory is not just a technician; he confronts the laws of nature as a child confronts the world of fairy tales. We do not have to make people believe that scientific progress can be reduced to a mechanism, to a machine: things which, moreover, have their beauty.

I do not believe that the spirit of the scientific enterprise threatens to disappear from our world. If there is something vital in everything that I notice, this is the spirit of adventure which seems inextinguishable and is bound up with curiosity. ✺

The sense of beauty in the world seems to be a basic requirement for bringing curiosity to bear and therefore for research. In fact, when interest in the object of one's study becomes enthusiasm, a source of incredible energy has been discovered. Here we are a long way from the fear of those who claim to be detaching reason as much as possible from a positive feeling for reality and the fascination that this provokes, so as not to risk disturbing the "objectivity" of knowledge.

Konrad Lorenz[9]

The magnificence and the beauty of this world must indeed be made readily accessible to the young people of today so that they are not left in any doubt about the present position of mankind and so that they are not left to despair. . . . It must somehow still be possible to make comprehensible to such young people that truth, too, is not only beautiful but also full of mind-boggling mystery, that one does not have to take drugs or become a mystic in order to experience the wondrous.

At a time when it has become fashionable to regard science as an essentially value-indifferent undertaking, it is understandable that the scientist feels obliged to demand of himself a value-free attitude toward his research subject or toward the object of his study. I regard this vogue as dangerous, however, because of its self-deception. For example, all of the biologists I know are undeniably lovers of their objects of study, in exactly the same sense that someone whose hobby is aquaria is in love with the objects being cared for.

Every human who can become sentient to and experience joy in creation and its beauty is made immune to any and every doubt about its meaning. . . . Speaking or writing about the beauties of the cosmos is a pleonasm since beauty, order and harmony are already subsumed in the meaning of the word cosmos. Close acquaintance with the beautiful precludes the erroneous belief . . . that only what can be exactly defined and neatly qualified is real. ✺

The beauty that captivates the scientist has something to do with the capacity of nature to show itself in an enormous variety of forms and different phenomena that depend on, or are compatible with, a small number of simple and synthetic laws. In the field of biology, for example, it is interesting to note that, on finishing his magnum opus *The Origin of Species*, Charles Darwin emphasized this very aspect as a characteristic of the new theory of evolution.

Charles Darwin[10]

There is grandeur in this view of life with its several powers, having been originally breathed by the Creator into a few forms or into one; and that, while this planet has gone circling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved.

The genius is the one who sees the essentials in a problem or in a situation. He is not unaware of the complexity but has the gift of recognizing the constitutive elements of the problem as it were by instinct. What appears to others as an inextricable tangle, for him assumes order and beauty.

Enrico Fermi[11]

My greatest impression of Fermi's method in theoretical physics was of its simplicity. He was able to analyze into its essentials every problem, however complicated it seemed to be. He stripped it of mathematical complications and of unnecessary formalism. In this way, often in half an hour or less, he could solve the essential physical problem involved. Of course there was not yet a mathematically complete solution, but when you left Fermi after one of these discussions, it was clear how the mathematical solution should proceed.

This method was particularly impressive to me because I had come from the school of Sommerfeld in Munich who proceeded in all his work by complete mathematical solution. Having grown up in Sommerfeld's school, I thought that the method to follow was to set up the differential equation for the problem (usually the Schrödinger equation[12]), to use your mathematical skill in finding a solution as accurate and elegant as possible, and then to discuss this solution. In the discussion, finally, you would find out the qualitative features of the solution, and hence understand the physics of the problem. Sommerfeld's way was a good one for many problems where the fundamental physics was already understood, but it was extremely laborious. It would usually take several months before you knew the answer to the question. The physics became clear by an analysis of the essentials, and a few order-of-magnitude estimates. His approach was pragmatic. . . .

Fermi was a good mathematician. Whenever it was required, he was able to do elaborate mathematics; however, he first wanted to make sure that this was worth doing. He was a master at achieving important results with a minimum of effort and mathematical apparatus.

By working in this manner he clarified the problems very much, especially for younger people who did not have his great knowledge. For instance, his formulation of quantum electrodynamics is so much simpler than the original one of Heisenberg and Pauli that it could be very easily understood. I was very much intimidated by the Heisenberg–Pauli article, and could not see the forest because of the trees. Fermi's formulation showed the forest. The same was true in the paper we wrote together, concerning the various formulations of relativistic collision theory. Fermi's formulation of neutron diffusion, the age theory, has been exceedingly fruitful in making quick calculations of neutron diffusion even in complicated cases. I could multiply this list easily, just from my own experience with Fermi and his work. ✺

The physicist feels an irresistible attraction to the simple law that involves a minimum number of concepts and that is capable of taking account of a great variety of apparently diverse and independent phenomena. This is the case with Newton's brilliant generalization, for which the same law of universal gravitation reflects both the fall of apples from trees and the movement of the moon around the earth. The original property of nature, that it can be read on the basis of simple synthetic principles, is the source of a secret and profound amazement. The progressive unification of the fundamental forces of physics (first electrical and magnetic, then weak-electrical and strong-electrical), arrived at in the century just past, offers a marvelous example of this ascent toward a hypothetical "final law"—probably unattainable—from which all the known laws of physics would be descended. But whether or not it is possible to achieve such a goal, the fact remains that the way of science always moves toward potent, bold, and elegant syntheses. The title of a book by the Nobel Prize–winner Steven Weinberg on this topic is symbolic: *Dreams of a Final Theory: Search for the Ultimate Laws of Nature*.

When we speak of the beauty of scientific theories or of the equations that represent them, we are not speaking of a superficial sense of self-satisfaction or a purely sentimental reaction. Rather, this is an indication of the truth of a kind that would probably have suited St. Thomas and that Weinberg indicates in the next passage.

Steven Weinberg[13]

In 1974 Paul Dirac came to Harvard to speak about his historic work as one of the founders of modern quantum electrodynamics. Toward the end of his talk he addressed himself to our graduate students and advised them to be concerned only with the beauty of their equations, not with what the equations mean. It was not good advice for students, but the search for beauty in physics was a theme that ran throughout Dirac's work and indeed through much of the history of physics.

Some of the talk about the importance of beauty in science has been little more than gushing. I do not propose . . . to say more nice things about beauty. Rather, I want to focus more closely on the nature of beauty in physical theories, on why our sense of beauty is sometimes a useful guide and sometimes not, and on how the usefulness of our sense of beauty is a sign of our progress toward a final theory.

A physicist who says that a theory is beautiful does not mean quite the same thing that would be meant in saying that a particular painting or a piece of music or poetry is beautiful. It is not merely a personal expression of aesthetic pleasure; it is much closer to what a horse trainer means when he looks at a racehorse and says that it is a beautiful horse. The horse trainer is of course expressing a personal opinion, but it is an opinion about an objective fact: that, on the basis of judgments that the trainer could not easily put into words, this is the kind of horse that wins races.

Of course, different horse trainers may judge a horse differently. That is what makes horse racing. But the horse trainer's aesthetic sense is a means to an objective end—the end of selecting horses that win races. The physicist's sense of beauty is also supposed to serve a purpose—it is supposed to help the physicist select ideas that help us to explain nature. Physicists, just as horse trainers, may be right or wrong in their judgments, but they are not merely enjoying themselves. They often are enjoying themselves, but that is not the whole purpose of their aesthetic judgments.

This comparison raises more questions than it answers. First, what is a beautiful theory? What are the characteristics of physical theories that give us a sense of beauty? A more difficult question: Why does the physicist's sense of beauty work, when it does work? The stories told . . . illustrated the rather spooky fact that something as personal and subjective as our sense of beauty helps us not only to invent physical theories but even to judge the validity of theories. Why are we blessed with such aesthetic insight? The effort to answer the question raises another question that is even more difficult, although perhaps it sounds trivial: What is it that the physicist wants to accomplish?

What is a beautiful theory? The curator of a large American art museum once became indignant at my use of the word "beauty" in connection with physics. He said that in his line of work professionals have stopped using this word because they realize how impossible it is to define. Long ago the physicist and mathematician Henri Poincaré admitted that "it may be very hard to define mathematical beauty, but that is just as true of beauty of all kinds."

I will not try to define beauty, any more than I would try to define love or fear. You do not define these things; you know them when you feel them. Later, after the fact, you may sometimes be able to say a little to describe them, as I will try to do here.

By the beauty of a physical theory, I certainly do not mean merely the mechanical beauty of its symbols on the printed page. The metaphysical poet Thomas Traherne took pains that his poems should make pretty patterns on the page, but this is no part of the business of physics. I should also distinguish the sort of beauty I am talking about here from the quality that mathematicians and physicists sometimes call elegance. An elegant proof or calculation is one that achieves a powerful result with a minimum of irrelevant complication. It is not important for the beauty of a theory that its equations should have elegant solutions. The equations of general relativity are notoriously difficult to solve except in the simplest situations, but this does not detract from the beauty of the theory itself. Einstein has been quoted as saying that scientists should leave elegance to tailors.

Simplicity is part of what I mean by beauty, but it is a simplicity of ideas, not simplicity of a mechanical sort that can be measured by counting equations or symbols. Both Einstein's and Newton's theories of gravitation involve equations that tell us the gravitational forces produced by any given amount of matter. In Newton's theory there are three of these equations (corresponding to the three dimensions of space)—in Einstein's theory there are fourteen. In itself, this cannot be counted as an aesthetic advantage of Newton's theory over Einstein's. And in fact it is Einstein's theory that is more beautiful, in part because of the simplicity of his central idea about the equivalence of gravitation and inertia. That is a judgment on which scientists have generally agreed, and as we have seen it was largely responsible for the early acceptance of Einstein's theory.

There is another quality besides simplicity that can make a physical theory beautiful—it is the sense of inevitability that the theory may give us. In listening to a piece of music or hearing a sonnet one sometimes feels an intense aesthetic pleasure at the sense that nothing in the work could be changed, that there is not one note or one word that you would want to have different. In Raphael's *Holy Family* the placement of every figure on the canvas is perfect. This may not be of all paintings in the world your favorite, but as you look at that painting, there is nothing that you would want Raphael to have done differently. The same is partly true (it is never more than partly true) of general relativity. Once you know the general physical principles adopted by Einstein, you understand that there is no other significantly different theory of gravitation to which Einstein could have been led. As Einstein said of general relativity, "The chief attraction of the theory lies in its logical completeness. If a single one of the conclusions drawn from it proves wrong, it must be given up; to modify it without destroying the whole structure seems to be impossible."

This is less true of Newton's theory of gravitation. Newton could have supposed that the gravitational force decreases with the inverse cube of distance rather than the inverse square if that is what the astronomical data had demanded, but Einstein could not have incorporated an inverse-cube law in his theory without scrapping its conceptual basis. Thus Einstein's fourteen equations have an inevitability and hence beauty that Newton's three equations lack. I think that this is what Einstein meant when he referred to the side of the equations that involve the gravitational field in his general theory of relativity as beautiful, as if made of marble, in contrast with the other side of the equations, referring to matter, which he said were still ugly, as if made of mere wood. The way that the gravitational field enters Einstein's equations is almost inevitable, but nothing in general relativity explained why matter takes the form it does.

The same sense of inevitability can be found (again, only in part) in our modern standard model of the strong and electro-weak forces that act on elementary particles. There is one common feature that gives both general relativity and the standard model most of their sense of inevitability and simplicity: they obey principles of symmetry.

Wonder and Contemplation: Tell It to the Rambler Roses, the Lindens, the Sun

The wonder of being confronted by nature does not just affect people's feelings, but affects them as a whole. Reason is, so to speak, paralyzed if it cannot attain a moment of contemplation and does not tend in some way to make contemplation itself deeper and more aware.

Mathematical research, too, has often been inspired from its first moments by a profound sense of the order, proportion, harmony, and beauty of the real. According to Federigo Enrìques, the earliest creations of pure mathematics produce the same aesthetic reaction as that felt at the beauty of a natural spectacle.

Federigo Enrìques[14]

If it is said that the object of mathematics—immanent order in nature—discloses itself to the mind by a process of abstraction, precisely for that reason mathematics is not just a science, a representation of that object, but also art, i.e., an expression of the subject who constructs it, according to its innermost laws. In particular it expresses the profound sense of order, or proportion and of measure, which makes the chaos of phenomena a cosmos.

Sailing round southern Italy and Sicily, the ancient Pythagoreans, contemplating by night the starry sky, attempted to express the distances of those distant stars in numerical harmonies which—as Plato says—are more beautiful than the wonders of the heavens in the visible world. And as if the universe were responding to their inner feeling, those harmonies little by little became for them a celestial music, inaudible to the ear that is accustomed to it, but present to the spirit of those contemplating, in the joyful peace of the spectacle. This is how the colorful historical tradition of poetry reports the feeling that inspired the first steps in mathematical research.

The enthusiasm that accompanies the discoveries of these poets must be understood in the etymological sense of the word, as the mystical ecstasy of someone who is sharing in a divine revelation. They communicated with the deity, in the same way as the Orphics, no longer in the drunkenness of the cult of Dionysius but in the beauty of the proportions and forms symbolized by Apollo.

Over the centuries the emotion of someone who has grasped a "note of the eternal poem" can still be felt in the language of the great mathematicians and mathematical physicists. Having recognized his third law on the motion of the planets (the squares of the periodic times are proportionate to the major axes of the elliptical orbits), Kepler (in the *Harmonices mundi*) uttered a hymn to his own discovery: "After eight months I saw the first ray of light, after three months I saw the dawn, and then one day the pure sun of the most admirable contemplation. Nothing held me back, and I could follow my enthusiasm. I want to confound mortals with the naïve confession that I have stripped the Egyptians of their golden vessels to make them into a tabernacle to my God, far from the frontiers of Egypt. . . . The dice were cast, and I wrote my book; it will be read today or tomorrow by posterity, it is not important when; it will be able to wait a hundred years for its readers because God has waited six thousand years for someone to contemplate his works."

Here the aesthetic impact is expressed as a confrontation with the beauty of a spectacle of nature. But this same impact accompanies the earliest creations of pure mathematics. János Bolyai, telling his father of his discovery of non-Euclidean geometry, wrote to him: "Out of nothing I have seen a new world." The mathematician has the feeling that the work of his creative imagination gives life to the fantasies evoked, as happens similarly to the poet. So Weierstrass could say that a "mathematician who does not have something of the poet in him will never be a complete mathematician."

And indeed in the more modest expressions of their authors, those who discover a mathematical truth look at it as an artist looks at his work; to those who contemplate it from outside, this always seems to be a work of beauty, when different concepts and properties come to fuse marvelously in a superior harmony of number and forms. ✺

So there is no mathematics without poetry. The mathematician finds himself contemplating the fruit of his own discovery. For a moment this happens to every discoverer, at least before pride tends to prevail and obscure the amazement. But in the specific case, the amazement of the mathematician at a theorem that has been demonstrated makes it all the clearer that the mathematician reaches a real objective level and is not reduced to an arbitrary construction of the imagination.

Some scientists, such as Francesco Redi, have explicitly expressed the dimension of wonder in the very way they describe their research. Respect for the experimental datum and care to take into account all the elements of the phenomenon observed without anything being omitted are fundamental attitudes, favored in an experimenter who is capable of feeling fascination for the reality that he or she observes, rather than with an indifferent attitude.

Francesco Redi[15]

For Redi, science still has an element of wisdom about it; it is a humanistic, not a technical science. At the basis of his research is the presupposition that life is a good, a value which arouses admiration and consent. The element of wonder in it proceeds from the recognition of a divine order in the world, whereas today the world tends to be considered as prime matter put at our disposal. Unlike many modern scientists, who are obsessed with a sense of horror at the cruelty to be found in the world or who accept unfeelingly the idea of a world reduced to a mechanism of pure chance, behind Redi's wonder there is a transcendent element, so that it comes directly from the admiration that he shows for the extraordinary miracle of life, whether animal, vegetable, or mineral, renewed every day before his questing eyes.

Thus for Redi the observer is an integral part of the observation: whereas he observes attentively (hence the very frequent use of verbs of perception) and experiments, assessing the data offered by the *senses* with reason, according to Galileo's experimental method, he is fascinated by the mystery of the universe which reveals, especially to his sense of sight, the ever new and diverse spectacle of an uninterrupted series of generations and natural metamorphoses (hence the equally frequent use of verbs of becoming).

. . . On the other hand, in Redi attention directed to experimental data is very often accompanied by a sense of amazement and wonder which expresses in the style of Galileo "not only the attitude of the ordinary person who observes a natural fact for the first time but the attitude of the scientist to all discoveries," i.e., his anxiety for truth in the face of the mystery of the universe and in this instance the extraordinary miracle—or spectacle—of the birth of life and its infinite transformations. The frequency with which words about "wonder" or words which speak of "becoming" occur could be attributed to that "descriptive meticulousness" in the style of Bartoli that many critics note in Redi's prose; but it seems to me that this is to be attributed more to a fundamental attitude of the scientist-writer, for whom the world is not reduced to the measure of human observations and the judgment of the human mind; while never yielding in his writings to suggestions of a metaphysical kind and always remaining faithful to empiricism, he gives the impression of feeling that beyond the phenomena there is a force that transcends them and thus transcends his observation and argumentation, based on trust in life, all of which stands in a tradition of love of life—that prompted by Galileo's speculation—in the sphere of which unfolds the element of wonder by which the precision of the observation of nature is intensified and as it were validated.

. . . The birth of frogs is an exemplary page, showing how the transformation, depicted in an urgent and rapid style, always remains perfectly framed in the visual field, with an attentive eye and shrewd observation:

"However, I have observed that when the frogs or toads are born in ditches and puddles they are born in the form of fishes, not just with front feet but without any feet, with a long, flat, so to speak sharp tail; and in this form they spend many days swimming, feeding and growing; they thus develop two front legs and, after a few more days, on the underside a skin which covers all their body outside the other two legs. After a certain time has passed they shed their tail, which does not divide into two parts as Pliny, Rondelezio, and so many other writers have believed. Anyone can ascertain this truth by examining with an anatomical scalpel frogs born after a few days, and will see that . . . it is possible to observe that . . ." ✺

The possibility of knowing nature exercises an irresistible attraction. The passion and trepidation of scientists in their everyday activity emerges clearly from this account by someone who was a direct witness of the work of Marie Curie. And there is no mistaking the tension in her research that determines her whole state of mind and provokes, in a moment of clarity, a desire to tell the whole world of the happiness that follows.

Marie Curie[16]

"I don't know whether I could live without the laboratory."

To understand this cry of confession we must see Marie Curie in front of her apparatus when, having finished her daily tasks, she could at last give herself over to her passion. No exceptional experiment was necessary to give this hollowed face a sublime expression of absorption and ecstasy. A difficult piece of glassblower's work that Marie brought off like an artist, a measurement well made, could give her the immensity of joy. An observant and sensitive collaborator, Mlle Chamié, was to describe this every-day Mme Curie, whose enraptured face was never to be caught by photography:

"She sat before the apparatus, making measurements in the half darkness of an unheated room to avoid variations in temperature. The series of operations—opening the apparatus, starting the chronometer, lifting the weight, etc.—was effected by Mme Curie with admirable discipline and harmony of movement. No pianist could accomplish what Mme Curie's hands accomplished with greater virtuosity. It was a perfect technique, which tended to reduce the coefficient of personal error to zero.

"After the calculations which Mme Curie made with eagerness, to compare the results, her sincere, undisguised joy could be seen because the margins of difference were much lower than the permitted limit, which assured the precision of the measurements. . . ."

Here is Mlle Chamié's description of her, absorbed in an experiment of capital importance: the preparation of actinium X for the spectrum of alpha rays—the last work Marie accomplished before her death:

"Actinum X had to be pure and in such a chemical state that it could not disengage its emanation. The working day was not long enough for the separation. Mme Curie remained at the laboratory that evening without dinner. But the separation of this element is slow: one had to pass the night at the laboratory, therefore, so that the intense source being prepared would not have time to 'decrease' much.

"It was two o'clock in the morning, and the last operation remained to be done: the centrifuge turned with a tiresome noise, but Mme Curie remained beside it without leaving the room. She contemplated the machine as if her ardent desire to make the experiment succeed could produce the precipitation of the actinium X by suggestion. Nothing existed for Mme Curie at this moment outside the centrifuge: neither her life of the morrow nor her fatigue. It was a complete depersonalization, a concentration of all her soul upon the work she was doing. . . ."

If the experiment did not give the hoped-for result, Marie suddenly seemed thunderstruck by some unknown disaster. Seated on a chair, her arms crossed, her back humped, her gaze empty, she suggested some old peasant woman, mute and desolate in a great grief. The collaborators who saw her were vaguely afraid some accident had happened, and inquired. Marie lugubriously pronounced the words that summed up everything: "We haven't been able to precipitate actinium X." Or else, sometimes she openly accused the enemy, thus:

"The polonium has a grudge against me."

But success made her light and young, fluttering. She wandered cheerfully in the garden, as if she wanted to tell the rambler roses and the lindens and the sun how happy she was. She was reconciled to science, she was ready to laugh and to marvel.

When a research worker, profiting by her evident good humor, proposed to show her a current experiment, she followed him eagerly, bent over the apparatus where the "numeration" atoms took place, and admired the sudden irradiation of a willemite ore by the action of radium.

Before these familiar miracles a supreme happiness was set alight in her ash-gray eyes. One might have said that Marie was gazing at a Botticelli or a Vermeer, the most enchanting picture in the world.

"Ah, what a pretty phenomenon!" she would murmur. ✳

Wonder and Curiosity: Toward a Limitless Frontier

What is the characteristic of the human being that makes the impact of amazement and wonder an active process, a capacity to formulate questions—in short, a cognitive process? With what word can we grasp the response of the scientist to the fascination of the real that invites him or her? Perhaps with the word "curiosity"? There is no research unless wonder turns into a question. And the raising of the question has roots in that attitude of elementary sympathy of the human being with reality that is indicated by the term curiosity. No one is a scientist who has not received an abundant share of "curiosity." Once again we find ourselves confronted with a dimension typical of the child, curious and interested in everything around it.

Curiosity is also the condition for the perpetuation of cognitive experiences in history, as the Nobel Prize–winner Sheldon Lee Glashow succinctly declared: "Fifty years ago Vannevar Bush correctly described science as the Limitless Frontier. It remains so, although we have learned since then. The adventure will continue as long as there are men and women in the world endued with curiosity."[17]

With their open attitude of curiosity, researchers are also struck by the smallest signals that come to them from nature, as Galileo describes them with simplicity in this passage. Galileo is here discussing the figure of the scientist who, following an almost stubborn curiosity, discovers new and diverse forms in which a certain phenomenon manifests itself; and it is by following the thrust of curiosity that he ultimately has to admit that new possibilities exist beyond those that he could have grasped.

Galileo Galilei[18]

There once lived, in a very solitary place, a man endowed by nature with extraordinary curiosity and a very penetrating mind. He raised many birds as a hobby, much enjoying their songs, and he used to observe with great admiration the happy contrivance by which they would transform at will the very air they breathed into a variety of sweet songs. Close to his house one evening, he chanced to hear a delicate sound, and, being unable to imagine what it could be except some small bird, he set out to capture it. Arriving at the road, he found a shepherd boy who was blowing into a kind of hollow stick and moving his fingers about on the wood, thus drawing from it a variety of notes similar to those of a bird, though by quite a different method. Puzzled, and led on by his natural curiosity, he gave the boy a calf in exchange for his recorder and retired to solitude. Realizing that if he had not chanced to meet the boy he would never have learned of the existence of two methods for forming musical notes and very sweet songs, he tried traveling far from his home in the hope of meeting with some new adventure. The very next day he happened to pass near a small hut, and, hearing a similar tone within, he went inside to find out whether it was a recorder or a blackbird. There he found a boy holding a bow in his right hand and sawing upon some fibres stretched upon a concave piece of wood. The fingers of the left hand (which supported the instrument) were moving, and without blowing the boy was drawing from it various notes, and most sweet ones too. Now, you who are participating in this man's mind and sharing in his curiosity, judge his astonishment! Finding himself to have two unexpected new ways of forming tones and melodies, he began to believe that still others might exist in nature. His wonder increased when upon entering a certain temple he glanced behind the gates to learn what it was that had sounded, and perceived that the noise had emanated from the hinges and fastenings as he had opened the gate. Again, impelled by curiosity, he entered an inn expecting to see someone lightly bowing the strings of a violin, and instead saw a man rubbing the tip of his finger round the rim of a goblet and drawing forth from it a very sweet sound. And later he observed that wasps, mosquitoes, and flies did not form separate notes from their breaths, as did his original birds, but made steady tones by the swift beating of their wings.

In proportion as his amazement grew, his belief diminished that he knew how sounds were created; nor could all his previous experience have sufficed to make him understand or even believe that crickets, which do not fly, could draw their sweet and sonorous shrilling not from breath but from a scraping of wings. And when he had almost come to believe that there could be no further ways of forming notes—after having observed in addition to what has been recounted numerous organs, trumpets, fifes, stringed instruments of various sorts, and even that little iron tongue which placed between the teeth makes strange use of the buccal cavity as a sounding box and of the breath as a vehicle of sound—when, I say, he believed that he had seen everything, he found himself more than ever wrapped in ignorance and bafflement upon capturing in his hand a cicada, for neither by closing its mouth nor by stopping its wings could he diminish its strident sound, and yet he could not see it move either its scales or any other parts. At length, lifting up the armor of its chest and seeing beneath this some thin, hard ligaments, he believed that the sound was coming from a shaking of these, and he resolved to break them in order to silence it. But everything failed until, driving the needle too deep, he transfixed the creature and took away its life with its voice, so that even then he could not make sure whether the song had originated in those ligaments. Thereupon his knowledge was reduced to such diffidence that when asked . . . how sounds are generated he used to reply tolerantly that although he knew some of the ways, he was certain that many more existed which were unknown and unimaginable. ✺

Modern scientists, too, recall that the beginning of their scientific adventure was dominated by curiosity. It is not unusual among researchers to recognize the rise of their own scientific "vocation" in the first indications of curiosity they had as children. And in such a way the development of scientific experience appears as the "realization of a dream," as Bruno Rossi relates.

Bruno Rossi[19]

I do not remember when my interest in science began. Perhaps there was not a beginning. Perhaps it evolved gradually from seeds which already existed in my childhood, in the form of a curiosity for the everyday wonders of nature—a blossoming plant, the small treasures on the beach left behind by the receding tide. Clearer evidence of a scientific disposition would come when later I began looking for regularities, for relations of cause and effect, and when I became conscious of the world which hides behind the world of our senses, and the behavior.

Even if what I say is not mere fantasy and even if there actually was in my nature an inborn tendency toward science, I know for certain that it was the influence of my father which turned this tendency into a lifelong commitment. . . .

. . . I arrived in Florence in early 1928, with a position of assistant to the professor of experimental physics at the University. . . .

I was eager to start working at some experimental project. But the ambition of the young scientist who does not see limits to his investigations did not allow me to settle for some run-of-the-mill program. My activity had to address itself to the fundamental problems of contemporary physics; it had to aim at the discovery of some secret of nature.

Month after month I pursued this dream. I remember that once, fascinated by the new horizons disclosed by Persico's lectures, Bernardini and I had decided to verify experimentally the predictions of wave mechanics by repeating, with slow electrons, one of the classical experiments of optical interference . . . (all we had to show for our efforts was a modest contribution to the study of the photographic effect of slow electrons). Not much more realistic, and equally doomed to failure, was an attempt to photograph the spectra of comet tails for the purpose of discovering their chemical composition. I was beginning to wonder whether my ambition had not led me into a blind alley and whether the time had not come to lower the aim. Fortunately I did not need to.

The initial period of my life as a would-be scientist, a period beset by uncertainties and saddened by disappointments, came to an end in the autumn of 1929, when I happened to read the historical article of the German physicists Walter Bothe and Walter Kohlhörster, *Das Wesen der Höhenstrahlung* (*The Nature of Radiation from Above*).

Until then I had not been much interested in the *Höhenstrahlung*, or *cosmic radiation*, to use the suggestive expression introduced by Robert Millikan. I did not see how I could find material for research in any aspect of this phenomenon. By then, the celestial origin of cosmic radiation had been established beyond any reasonable doubt. . . . But I was skeptical because, in my opinion, the interpretation of the experimental observations on which Millikan had built his theory was not convincing. On the other hand, I did not see how, being an experimentalist, I could contribute significantly to the current speculations about the origin of cosmic rays. Lastly, there was the problem of the nature of cosmic rays. But the problem was not of much concern because, according to the general view, the answer was already known. The argument ran as follows: cosmic rays were known to have a penetrating power far exceeding that of any other known rays. Of these, the most penetrating were the gamma rays of some radioactive sources. Moreover, according to current theories, the penetrating power of gamma rays was expected to increase steadily with increasing energy. Therefore, the astonishingly penetrating cosmic rays could not be anything else but gamma rays of very great energy.

For the first time, the gamma-ray hypothesis was submitted to an experimental test of Bothe and Kohlhörster. In their experiment they used an instrument that had just been developed by the well-known German physicist Hans Geiger and his pupil William Müller. I am referring to the *tube counter*. . . . While the ionization chamber,[20] used previously in cosmic ray studies, measures the total ionization of all particles which traverse its sensitive volume in a given time interval, the counter signals, with an electric pulse, the arrival of every single ionizing particle. . . .

I, for one, focused my attention on the new problems created by this discovery. What, actually, were the particles found in cosmic rays? Were they particles of the same kind as those already known, only endowed with much greater energies? Or were they particles of a different, new kind? And, in either case, what were their physical properties? . . .

I started working immediately with the generous support of my friends in the group. And so began one of the most exhilarating periods of my life. Was it the excitement of the explorer who first ventures into an unknown land? Was it the companionship of people with whom I could share my enthusiasm, my hopes, my anxieties? Was it the subtle charm of the Tuscan countryside?

The daughter of Karl Jansky, the American engineer who was the first to identify radio waves of astrophysical origin coming from the Milky Way, has a vivid memory of the way in which he involved his family in his enthusiasm for the “event” of nature. It is difficult to think that such an attitude of lively curiosity was not crucial for Karl in his historic and unprogrammed discovery of radio-astronomy.

Karl Jansky[21]

I can’t pinpoint the beginnings of my father’s interest in astronomy, whether or not it predated his discovery, but I know that it persisted afterward through my childhood. He had some basic references on astronomy, including a star atlas, which I loved to read, and, according to my mother, he owned all the textbooks used at the time in the astronomy courses at Princeton, and read them avidly.

One probable effect of his informal pursuits in astronomy was his habit of dragging us all out of bed in the middle of the night to gaze at some celestial phenomenon. On such a night I would gradually awaken to the realization that Daddy was pacing back and forth in my bedroom, leaning far out of one after the other of the windows, which were the only ones upstairs with an uncluttered view of the sky. Then, at the right moment for viewing the "event," he would get me up, and I would run outside with him, while my mother would try to get my brother out of bed. This was always quite traumatic for David, who always resisted any interference with his sleep, and would thrash around in his bed, objecting vociferously to my mother's pleading. She'd call, "Karl, David doesn't want to wake up!" My father would call back from out on the front lawn, "Well, you've just got to get that boy up—he may never get a chance to see this again in his entire life!" Finally, we'd all stand outside, with or without David, depending on who won the battle. Shivering in our pajamas, we'd watch an eclipse of the moon or a colorful display of the aurora borealis. Another identification of his interest was a black box device he made and set up on the front stoop, which enabled us to see sunspots.

My father had a natural curiosity that was evident in our daily life. . . .

Wonder and Knowledge: Hunting Signs

The wonder evoked by reality goes hand in hand with the desire to understand, to explore the possibilities that nature offers. The world is "out yonder," with its call.

Albert Einstein[22]

It is quite clear to me that the religious paradise of youth, which was thus lost, was a first attempt to free myself from the chains of the "merely personal," from an existence dominated by wishes, hopes, and primitive feelings. Out yonder there was this huge world, which exists independently of us human beings and which stands before us like a great, eternal riddle, at least partially accessible to our inspection and thinking.

The mental grasp of this extra-personal world within the frame of our capabilities presented itself to my mind, half consciously, half unconsciously, as a supreme goal. Similarly motivated men of the present and of the past, as well as the insights they had achieved, were the friends who could not be lost. The road to this paradise was not as comfortable and alluring as the road to the religious paradise; but it has shown itself reliable, and I have never regretted having chosen it. ✺

What prompts the search for new theories? The fact is, as Einstein says here, that we human beings "enjoy comprehending." It is a passion for understanding, for knowing the truth (some fragment of truth, perhaps even a grain of truth gained with great effort and expenditure of energy), without which there would be no reason for the scientific enterprise. Just as the record industry and musical instruments are not enough to explain the passion of so many people for music, so all the technological and economic consequences of scientific research do not explain the love of contemplating nature that moves the individual scientist (the contrary would be the case: if there were no passion for music, the musical instrument industry would inevitably tend to disappear). Einstein concludes that the elaboration of a theory on the one hand cannot leave out experience and on the other does not derive mechanically from it but calls for the creative act of the subject.

Albert Einstein[23]

The editors of *Scientific American* have asked me to write about my recent work which has just been published. It is a mathematical investigation concerning the foundations of field physics.

Some readers may be puzzled: Didn't we learn all about physics when we were still at school? The answer is "yes" or "no," depending on the interpretation. We have become acquainted with concepts and general relations that enable us to comprehend an immense range of experiences and make them accessible to mathematical treatment. In a certain sense these concepts and relations are probably even final. This is true, for example, of the laws of light refraction, of the relations of classical thermodynamics as far as it is based on the concepts of pressure, volume, temperature, heat and work, and of the hypothesis of the non-existence of a perpetual motion machine.

What then impels us to devise theory after theory? Why do we devise theories at all? The answer to the latter question is simply: Because we enjoy "comprehending," i.e., reducing phenomena by the process of logic to something already known or (apparently) evident. New theories are first of all necessary when we encounter new facts which cannot be "explained" by existing theories. But this motivation for setting up new theories is, so to speak, trivial, imposed from without. There is another, more subtle motive of no less importance. This is the striving toward unification and simplification of the premises of the theory as a whole (i.e., Mach's principle of economy, interpreted as a logical principle).

There exists a passion for comprehension, just as there exists a passion for music. That passion is rather common in children, but gets lost in most people later on. Without this passion there would be neither mathematicians nor natural science. Time and again the passion for science has led to the illusion that man is able to comprehend the objective world rationally, by pure thought, without any empirical foundations—in short, by metaphysics. I believe that every true theorist is a kind of tamed metaphysicist, no matter how pure a "positivist" he may fancy himself. The metaphysicist believes that the logically simple is also the real. The tamed metaphysicist believes that not all that is logically simple is embodied in experienced reality, but that the totality of all sensory experience can be "comprehended" on the basis of a conceptual system built on premises of great simplicity. The sceptic will say that this is a "miracle creed." Admittedly so, but it is a miracle creed which has been borne out to an amazing extent by the development of science.

The rise of atomism is a good example. How may Leucippus have conceived this bold idea? When water freezes and becomes ice—apparently something entirely different from water—why is it that the thawing of ice forms something which seems indistinguishable from the original water? Leucippus is puzzled and looks for an "explanation." He is driven to the conclusion that in these transitions the "essence" of the thing has not changed at all. Maybe the thing consists of immutable particles and the change is only a change in their spatial arrangement. Could it not be that the same is true of all material objects which emerge again and again with nearly identical qualities?

This idea is not entirely lost during the long hibernation of occidental thought. Two thousand years after Leucippus, Bernoulli wonders why gas exerts pressure on the walls of a container. Should this be "explained" by mutual expulsion of the parts of the gas, in the sense of Newtonian mechanics? This hypothesis appears absurd, for the gas pressure depends on the temperature, all other things being equal. To assume that the Newtonian forces of interaction depend on temperature is contrary to the spirit of Newtonian mechanics. Since Bernoulli is aware of the concept of atomism, he is bound to conclude that the atoms (or molecules) collide with the walls of the container and in doing so exert pressure. After all, one has to assume that atoms are in motion; how else can one account for the varying temperature of gases?

A simple mechanical consideration shows that this pressure depends only on the kinetic energy of the particles and on their density in space. This should have led the physicists of that age to the conclusion that heat consists in random motion of the atoms. Had they taken this consideration as seriously as it deserved to be taken, the development of the theory of heat—in particular the discovery of the equivalence of heat and mechanical energy—would have been considerably facilitated.

This example is meant to illustrate two things. The theoretical idea (atomism in this case) does not arise apart and independent of experience; nor can it be derived from experience by a purely logical procedure. It is produced by a creative act. ✺

Galileo's analogy of the scientist as a reader of the book of nature is famous: the language in which the book is written is a mathematical language. Einstein, in the famous popular text written with Leopold Infeld, took up Galileo's image, suggesting moreover that the style of the book is that of a detective story and that the scientist- reader is in a position not only to possess the appropriate language for deciphering the characters—mathematics—but also to discover the mystery in the plot. Einstein was convinced that there are physical laws at our disposal that describe nature as it really is and are not a simple approximation of it, but he was also convinced that the final solution of the mystery is still a long way off. He also admitted that it seems to go further away the more that investigations advance. That does not prevent admiration of the beauty of the "perfect construction of the book."

Albert Einstein and Leopold Infeld[24]

In imagination there exists the perfect mystery story. Such a story presents all the essential clews, and compels us to form our own theory of the case. If we follow the plot carefully we arrive at the complete solution for ourselves just before the author's disclosure at the end of the book. The solution itself, contrary to those of inferior mysteries, does not disappoint us; moreover, it appears at the very moment we expect it.

Can we liken the reader of such a book to the scientists, who throughout successive generations continue to seek solutions of the mysteries in the book of nature? The comparison is false and will have to be abandoned later, but it has a modicum of justification which may be extended and modified to make it more appropriate to the endeavor of science to solve the mystery of the universe.

This great mystery story is still unsolved. We cannot even be sure that it has a final solution. The reading has already given us much; it has taught us the rudiments of the language of nature; it has enabled us to understand many of the clews, and has been a source of joy and excitement in the oftentimes painful advances of science. But we realize that in spite of all the volumes read and understood we are still far from a complete solution, if, indeed, such a thing exists at all. At every stage we try to find an explanation consistent with the clews already discovered. Tentatively accepted theories have explained many of the facts, but no general solution compatible with all known clews has yet been evolved. Very often a seemingly perfect theory has proved inadequate in the light of further reading. New facts appear, contradicting the theory or unexplained by it. The more we read, the more fully do we appreciate the perfect construction of the book, even though a complete solution seems to recede as we advance. ✺

Max Planck explicitly affirmed that the taste and satisfaction of the researcher lie in advancing, in taking a further step forward in penetrating the unknown, rather than in the illusory objective of an absolute final knowledge.

Max Planck[25]

My original decision to devote myself to science was a direct result of the discovery which has never ceased to fill me with enthusiasm since my early youth—the comprehension of the far from obvious fact that the laws of human reasoning coincide with the laws governing the sequences of the impressions we receive from the world about us; that, therefore, pure reasoning can enable man to gain an insight into the mechanism of the latter. In this connection, it is of paramount importance that the outside world is something independent from man, something absolute, and the quest for the laws which apply to this absolute appeared to me as the most sublime scientific pursuit in life. ✺

Wonder and Joy: Flammanda Moenia Mundi

In the course of the activity of research, this same attitude of amazed admiration of reality translates into the capacity to recognize the new that emerges, the joy of discovery. The discovery of the new by a scientist can become a source of joy for all. This is because the individual researcher is not isolated, but works within the context of human company. Ideally the scientist enjoys discovery, even if it is made by someone else. Certainly, reality is often more prosaic, studded with envy, ill will, and petty betrayals—as in any other field of human activity. But it is undeniable that this passage from John Archibald Wheeler captures a genuine and real aspect of the scientific community: confronted with the spectacle of new evidence, in the scientist there is space for an instant of authentic contemplation.

John Archibald Wheeler[26]

Nothing more strongly animates this book than a passionate belief that this is our universe, our museum of wonder and beauty, our cathedral. Marvelous are the seamounts and the geysers of the ocean floor. Dream-provoking are the buried cities of the past. Awe-inspiring are the continental drift that steadily tears Iceland apart and the fiery furnaces that we call stars. The pace of exploration grows swifter with each passing decade. We celebrate each new finding, each new glory, each new wonder. They are the rightful inheritance of every thinking human.

The wonders found take second place to those still waiting to be found. The undiscovered lies around us in every direction, at what the ancient Romans liked to call "the flaming ramparts of the world," *flammanda moena mundi*. How humbling it is to realize that we, today, knowing so little about the world and ourselves, live still in the childhood of mankind. Yet what a joy! What a challenge! It is not surprising that the greeting between eager searchers of the unknown is often not "Hello," not "How are you," but "What's new?"

Each year brings new findings about the mechanism of inheritance, the structure of matter, the workings of the brain, and many another active frontier. How happy it is for the interested inquirer from the larger community when the new result links familiar, everyday observations with some deep insight into the machinery of existence. . . .

In more sensitive scientists, admiration for the greatness of discoveries, their own and those of others, does not lead to proud affirmation or to the claimed omnipotence of human cognitive capacities; rather, it goes with an awareness of how much remains to be known.

Just as the child is an "expert" in wonder, so too is the great scientist. Isaac Newton identifies it with the clear and simple gaze of the child, a gaze that also identifies its way of "observing" things and noting their presence on the shore of the ocean of mystery.

Isaac Newton[27]

I don't know what I may seem to the world, but, as to myself, I seem to have been only like a boy playing on the sea shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me. ✺

Wonder and Observation: The Desire to See More

Wonder becomes a desire to see more, to scrutinize, to observe detail; and in its turn, observation increases wonder. It is the experience related by a passionate "photographer" of nature such as Leonardo, who put his great capacity for observation at the root of artistic, technical, and scientific creativity.

Leonardo da Vinci[28]

And drawn by my yearning desire I went to see the great cup of the various and strange forms made by natural artifice, descending beneath shadowy rocks. I reached the entrance to a great cavern in front of which I remained somewhat amazed and ignorant of such a thing. I bent my back and put my tired hand on my knee, and with my right hand I brought darkness to my lowered and closed eyes; and often bent here and there to see if anything was to be discerned within; this was forbidden me by the great obscurity which was there. And after I stayed awhile, there arose in me two things, fear and desire—fear because of the menacing dark cave, and desire to see whether there were any miraculous things within. ✺

Observation 2

Perhaps the first rule that I must make for myself is to pay attention to what I see. **ITALO CALVINO**

Personal observation and direct examination increase the capacity to record and distinguish facts and also to identify objects. . . . There is a greater advantage and a greater incentive in collecting data than simply reading them in books. **AL-BIRUNI**

The history of natural science can be summed up as the development of ever more perfect eyes within a world in which there is always something more to see. **PIERRE TEILHARD DE CHARDIN**

OBSERVATION IS a crucial aspect of the dynamic of cognition, not only in the field of science. Knowing how to observe requires a certain disposition, work, training, at least equal to that required for the analytical development of a hypothesis. Observing is not the same as seeing, if by "seeing" we understand the mere capacity to note an external event through the eyes, the brain, and all the physiology involved. Bees and lizards also have the capacity to see, and the visual system of leopards extends to regions of the electromagnetic spectrum that go far beyond what the human eye can sense. But in human beings, "seeing" can be something much greater and more profound. The level of seeing that we call "observation" implies looking at the object in a perspective of meaning that goes beyond simply noting the data. Perhaps we can say that observing means looking with a possibility of knowing what we are looking at. It is an interested seeing, which is the prelude to a closer and more profound relationship between the subject and the object. In a very rudimentary sense, leopards also observe when they look around the savannah intent on identifying their prey. This is only a distant analogy of what happens with the human being; human observation implies the hope (implicit or explicit) of knowing, possessing, "capturing" the object, namely grasping its link with the totality of things.

Let's imagine a place in the mountains in a summer month, with numerous tourists enjoying the view of the summit of the mountain that towers above them. Among them is one person who is evidently looking at the mountain in a different way from the others: he is an expert Alpinist who is looking at the mountain face that he has to climb for the first time. He is trying to decide what route to follow. He is seeking to grasp the profile of the ridges of rock, the most demanding routes, and to evaluate the risk involved in every possible choice of route. In doing this he is collecting a large number of details (gorges, crests, snowfields) that completely escape the view of tourists who are relaxing in the square on that splendid sunny morning. Aspects of the rock face that seem insignificant at first glance can be a matter of life and death for him. The Alpinist stands "observing" the mountain—that is, looking at it in accordance with a hypothesis, a purpose, a desire that moves him. It should be noted that precisely because his looking at the mountain implies his "deep" involvement with it, he has to try to respect to the full the reality of the face as it presents itself to him, trying at every moment not to allow his evaluation to be dominated by his own prejudices. It would be quite dangerous for him to judge at this distance a route that might then prove impracticable. The Alpinist will do everything to ensure that his observation is objective and secure. So he will not be content with observing the mountain from the square, like all the others, but will take the trouble to go some kilometers in one direction or another, to climb surrounding high points, to look for other points of view from which certain details can stand out more clearly, and new indications come into view.

The observation of real data is the basis for attaining the truth in any field of human knowledge. That is (or should be) inevitable in the scientific method. One observes by capturing the object. But one desires to "capture" the object because in some way one has already been captured by it. Why climb the mountain? There is a fascination that this summit has exercised and still exercises on our Alpinist, an attraction that demands his energies and draws the attention of his enquiring gaze to the rock face. It is the same with the scientist. Why try to get to know the laws of electromagnetism or the high-energy phenomena that take place in the first moments of the history of the universe? Researchers necessarily direct all their attention toward something that attracts them, something that has prompted their consciousness to become interested. It is not possible truly to observe an object unless one has a genuine interest in it. The Alpinist would find it difficult to determine the route of his ascent on the basis of data collected from someone selected by chance from among the tourists and paid by the hour to look at the details of the mountain from where he was; quite apart from any lack of experience, the tourist would not have the necessary interest in observing with due attention and objectivity. In this sense, paradoxically, it is important to be very interested in the object in order to observe it objectively.

Of course, observation is not without risks and possible, even extraordinary, errors. In fact, as I have indicated, the emotional resources of the subject need in some way to be directed toward the tension in observing and knowing the object "as it is," not in confirming the idea that in some way one has of it. In one of its various aspects, prejudice is always lying in wait with its capacity to distort and complicate the delicate and fascinating moment of observation. The researcher cannot free oneself completely from the risk of prejudice about what one is observing. Moreover, the line that separates the hypothesis from the preconception is sometimes so fine as to disappear completely (we return to this point in the next chapter). Thus, sometimes one can fail to see things that are before one's eyes or—even more remarkably—one comes to see things that in fact are not there: as we shall see, the history of science is full of famous examples. These are not situations in which the scientist is taken off track by the prospect of personal benefit but rather an authentic "suggestion" that leads to an involuntary distortion of the observation of facts.

On the other hand, scientific investigation normally advances through observations that are at the limit of the possibility of measuring instruments, whether the human eye or a powerful radio telescope. The innovations, the discoveries introduced by new experiments, are usually at the extreme limit of the sensitivity of our equipment. For this reason, even a bit of prejudice can lead different groups of researchers to support diametrically opposed hypotheses. Only in time, with the accumulation of indications, observations, and new evidence, can the real data finally emerge with clarity before the eyes of all.

Observation and Affection: Looking at the World As If for the First Time

Normally it is thought, and often affirmed, that for scientists to do their work well they must be as disinterested as possible in the object that they are studying. In reality, it seems that the opposite is the case. There cannot be attentive observation capable of grasping the most hidden subtlety without looking at a "dear" object, a reality that is prized and in some way "loved." Perhaps some scientists could be reluctant to recognize this openly, but basically attention to what one is observing and studying stems from an affective involvement with the object of the investigation. And this goes for all objects of research: the position that Konrad Lorenz describes here for the study of animals could equally represent that of chemists who study the geometry of crystals, or physicists who study the intimate symmetries of elementary particles, or astronomers who devote themselves to stellar evolution. In this involvement of one's affection lies the motive force for the beginning of research and the motivation that sustains it over time. The perseverance required by scientific investigation can in fact put the most unshakeable patience to the test.

Konrad Lorenz[1]

It was at that very moment that the thought of writing a book first crossed my mind. There was nobody to appreciate the joke, Alfred being far too preoccupied with his work. I wanted to tell it to somebody and so it occurred to me to tell it to everybody.

And why not? Why should not the comparative ethnologist who makes it his business to know animals more thoroughly than anybody else tell stories about their private lives? Every scientist should, after all, regard it as his duty to tell the public, in a generally intelligible way, about what he is doing.

There are already many books about animals, both good and bad, true and false, so one more book of true stories cannot do much harm. I am not contending, though, that a good book must unconditionally be a true one. The mental development of my own early childhood was, without any doubt, influenced in a most beneficial way by two books of animal stories which cannot, even in a very loose sense, be regarded as true. Neither Selma Lagerlof's *Nils Hogersson*, nor Rudyard Kipling's *Jungle Books* contain anything like scientific truth about animals. But poets such as the authors of these books may well avail themselves of poetic licence to present the animal in a way far divergent from scientific truth. They may daringly let the animal speak like a human being, they may even ascribe human motives to its actions, and yet succeed in retaining the general style of the wild creature. Surprisingly enough, they convey a true impression of what a wild animal is like, although they are telling fairy tales. In reading those books, one feels that if an experienced old wild goose or a wise black panther could talk, they would say exactly the things which Selma Lagerlof's Akka or Rudyard Kipling's Bagheera say.

The creative writer, in depicting an animal's behaviour, is under no greater obligation to keep within the bounds of exact truth than is the painter or the sculptor in shaping an animal's likeness. But all three artists must regard it as their most sacred duty to be properly instructed regarding those particulars in which they deviate from the actual facts. They must indeed be even better informed on these details than on others which they render in a manner true to nature. There is no greater sin against the spirit of true art, no more contemptible dilettantism than to use artistic licence as a specious cover for ignorance of fact.

I am a scientist and not a poet and I shall not aspire in this little book to improve on nature by taking any artistic liberties. Any such attempt would certainly have the opposite effect, and my only chance of writing something not entirely devoid of charm lies in strict adherence to scientific fact. Thus, by modestly keeping to the methods of my own craft, I may hope to convey, to my kindly reader, at least a slight inkling of the infinite beauty of our fellow creatures and their life.

Scientific observation is not the production of a long list of details, like an interminable collection of photographs, but a creative act in which the human gaze interrogates reality and brings together what it sees in accordance with a possible perspective of order and beauty. Here the profound analogy between scientific discovery and artistic creation returns. To observe an object or a natural phenomenon means noticing it (looking at it, seeing it) and turning tirelessly to examine it according to a hypothesis or a question of meaning and thus of a link with totality. Normally this means going in search of a general law or a synthetic principle capable of unveiling a deeper and richer relationship between the individual phenomenon observed and the enormous variety of phenomena analogous to it. Scientific experience, beginning with the observation of data, continually calls for this creative tension. The application of good rules or procedures is not enough for being a scientist—nor even for being an artist or a child. As with the artist or the child, the researcher is immersed in play with reality, and does not know how to observe without creating a link with his context. The dialectic between observation and creativity, between play and work, emerges in this clear reflection by the chemist and physicist John C. Polanyi.

John C. Polanyi[2]

The arts and the sciences are interdependent; there is a clear similarity in the aim of both and a very subtle similarity in method. The objective, whether of the artist or the scientist, is to give form to the surrounding world. Both do that by seeking configurations which bring together experiences that hitherto have been unconnected; both are driven by the same impulse: by the desire to learn or, to put it in a different way, to discover.

The child is a passionate discoverer. Children devote themselves to inventing a whole system of physics, governed by shape, color, consistence, dimensions, and permanence—to mention just some of the properties which come to them to define and put in relationships. They do this through what we call "games," simply because this is a process which we do not know how to rationalize. In fact they do not submit to logic. Children do not know the difference between work and play. In this they are like artists and scientists.

The artist and the scientist who dedicate themselves to fundamental research share an important experience: both are accused of playing instead of working. The wider public disapproves of those who play during working hours because they believe that playing is easy and devoid of social value. That is not true. Play is demanding and performs a vital social function: it makes discovery possible.

How is play essential to the process of discovery? That is a tricky question. . . . To be brief, the creative act for the artist and its equivalent for the scientist, the act of discovery, must—like play—go beyond the formal rules. There are no instruction manuals for the artist and for the scientist.

Obviously, one can always provide guidelines. For the painter, these relate to color and composition; in my profession to scientific method and proof. However, these fixed procedures in which the brain gives systematic instructions to the hand cease to be useful and one soon reaches stalemate. Then it is important to play, to let the hand control the brain and not vice versa. People deserve to be defined as creative when they do not limit themselves to applying existing rules but create new ones. A regulation does not accept this; a game does.

Here it is implicit that, like the artist, the scientist is involved in a "creative act." But, one might object, should we not be noting what is happening in nature?

In reality the scientist does not know how to report without interpretation, any more than a painter does. The fixed look of the scientific observer, if examined more closely, is simply an instrument for drawing, a brush. A laser beam reflected from the surface of the eye shows how this involuntarily depicts the object that it is looking at.

. . . We are continually depicting the world, and putting it into a configuration of our choice. Traditionally, the choice of the scientist is reductionist: he looks for a means of reducing the rich and complex nuances of nature to a simpler form, just as the artist has to reduce a three-dimensional form to the two dimensions of a picture.

[In a famous etching] Albrecht Dürer shows an artist reducing a voluptuous figure to some points in the bidimensional space of the picture. Is this a scientific enterprise, or is it art? And is it worth bothering to distinguish one from the other?

Certainly, the enterprise would seem to be sadly dispassionate. Probably that is enough to bring it under the heading of science. But not for me: in my experience science is a passionate enterprise. It is enough to think of Leonardo da Vinci who, as a meticulous scientific observer, passionately contemplates the fetus in its mother's womb. What he has seen and expressed in his anatomical drawings is not only a catalogue of elements but a unity of forms, a symphony of spheres.

Any painter of importance cannot do more than at least make his own comment on the human condition which on a small scale modifies it. That is what we expect from a painter. But I note that the scientist does something different and perhaps even more. In fact the observations of science have great repercussions and provoke changes of historical scope.

That is why courage is needed to be an innovator, whether in art or in science. Both disciplines—both means of knowledge—call on one to emerge from lethargy and look at the world as it were for the first time. ✺

Scientific observation is built on the conviction that nature abounds in information and offers indications to anyone who encounters it with a desire to find traces of the truth. Such a conviction translates in practice into attention in collecting even the minimal particulars of phenomena. Among the great observers, such as Mendel or Herschel, it presents itself as a capacity to discover some significant detail, some relevant particular that allows us to have a new understanding and a sense of all the other particulars.

Gregor Mendel[3]

On October 13, 1870, two and a half years after Mendel became abbot, a freak tornado raged through Brünn. As he watched the wind whip across the courtyard, sending furniture flying, tearing apart trees and outbuildings, the meteorologist in him went into high gear. He paid attention, as any good scientist would, to every minor detail of nature's fury.

The air roared a "hellish symphony," Mendel wrote less than a month later, "accompanied by the crash of window-panes and slates, which in some cases were flung through shattered windows to the other side of the room." As he sat near the window in his study, he watched a piece of roof slate fly through his open doorway, hurtle across his desk, and pass into the next room. But despite the "terrifying" nature of the brief cyclone—Mendel calculated that it swept through his immediate vicinity for no more than four or five seconds—the abbot was able to make detailed observations, and to record them with his typical care.

"The storm consisted of two gigantic cones," he told the Brünn Society of Natural Sciences in a lecture on November 9, 1870, "the upper of which had its point directed downward, and it seemed to hang from an isolated roundish mass of clouds, not very large, a mass in which a marked unrest, a vigorous to-and-fro movement was noticeable." He described the upper and lower cones, their shape, their coloration—and observed that, contrary to expectations, the tornado most definitely was spinning clockwise.

"This brings to an end the discussion of our dangerous guest," Mendel said in closing. "But we must admit that, however we have tried, we have got no further than an airy hypothesis, which is explained from airy material and on an airy basis."

The abbot's light tone, typical of his informal discourses but missing from his earlier scientific lectures, indicates that perhaps he did not take this tornado account quite as seriously as he had taken his earlier lectures on crossbreeding and the laws of inheritance. Or maybe it indicates simply that Mendel was older and wiser, aware finally that no matter how straight and earnest you were, no matter how much you comported yourself according to the rules, sometimes things just didn't work out the way you expected them to, and to your contemporaries you turned out to be virtually invisible.

The biggest surprise was the precision, and the irony, of the storm's damage. Almost as though his two great loves, horticulture and meteorology, were waging war, the cyclone was most devastating to one particular structure on the monastery property: Mendel's greenhouse. Did it break his heart to see that the whirlwind—which many people in those days believed to be the work of the devil—turned his beloved greenhouse, to which he still held out the hope of returning, into a splintered ruin? Or did he realize that his idyll in the greenhouse was already over, that it ended years before, when the steady thrum of activity that had breathed life into its humid air was stilled by circumstance and disappointment?

If Mendel was brokenhearted, he managed still to describe every nuance of the whirlwind with the same care he had used five years earlier to describe his peas. Both accounts relied on clear observation and an almost naïve faith in the power of description to uncover the telling detail, the one that would somehow enable all the other details to fall into place. . . . ✺

William Herschel[4]

This method of viewing the heavens seems to throw them into a new kind of light. They are now seen to resemble a luxuriant garden, which contains the greatest variety of productions, in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration. For, to continue the simile I have borrowed from the vegetable kingdom, is it not always the same thing, whether we live successively to witness the germinations, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once to our view? ✺

In observation, the possibility of resolving a problem emerges from the continual and subtle interplay between the view of the whole and that of the particular. The emotion of the researcher is set in motion simultaneously at both poles, that of the particular and that of the whole.

BARBARA MCCLINTOCK[5]

I was certain of being able to understand what the corn plant did when I had the whole in view and did not allow myself to be influenced by individual effects. But I also had to observe the local phenomena. Everywhere there were many mutations, and I was struck by the ear of corn, which presented a number of mutations greater than that of the whole plant. Every sector of the ear originated in a single cell, and this was the key which was to lead me to the solution. In the first cellular divisions something had to follow, and in particular something which made a cell obtain what another lost. A cell receives what another cell has lost. I immediately thought that I had found the solution.

Observation and Preconception: Losing Sight of What One Has before One's Eyes

The passion for reality brings the desire for knowledge to be authentic, for the true nature of the object under investigation to emerge. The main obstacle is an inevitable component of the preconception, which like a force of friction opposes mere adherence to the facts as they are. As Peter B. Medawar has written, to avoid any error it is necessary to "observe nature as a child does, without prejudices and preconceptions, but with that clear and candid vision which adults lose and scientists must strive to regain."[6] It is not possible to avoid this level of prejudice completely. The moral problem that arises for the scientist is not that of reducing one's own prejudice to zero, but of being more attracted by the desire to discover the true nature of the object than being attached to the idea of it that one already has.[7]

The prejudice can present itself in different forms; the most radical and dangerous for science is the temptation to think that only that exists which one has succeeded in seeing, and vice versa, that what one has not yet seen does not exist. Already in the sixteenth century, one of the founders of modern biology, Lazzaro Spallanzani, warned against the temptation to interpret an experiment in a preconceived way, thus precluding access to true knowledge: "The spirit of the inventor, daring and lively, is not always sufficiently restrained and circumspect. . . . I often believe that I see phenomena which in reality do not exist, but which I would like to exist."[8]

But Pasteur, too, wanted to put at the head of his *Études sur la bière* this telling statement by Bossuet: "The greatest disorder of the spirit is to believe in the existence of things that one wants to see."

Peter B. Medawar[9]

. . . I can remember forming the opinion, as a young research worker, that cells long maintained in culture outside the body undergo a transformation into the cancerous state, but dropped it because of the mistaken belief that transplantation experiments had already proved the idea untenable. My reasoning was that, if long-cultivated cells were in fact malignant (as many are now known to be), they should grow progressively, as malignant tumors do, when reimplanted into the body. In fact they did not do so, so the hypothesis was disproved. Unfortunately the act of disproof was itself erroneous: we now know that such a test could only have been valid if the cultivated cells contained no transplantation antigens not also present in the organism into which they were implanted; and even this test would have been unreliable if the cultivated cells had acquired new tumor-specific antigens during their growth outside the body. It is indeed true that ". . . disproof of a hypothesis is contingent on the stability of the theories employed in interpreting matters of fact, so that the refutation of a supposed explanation may be no more definitive than is its verification."[10]

We scientists often miss things that are "staring us in the face" because they do not enter into our conception of what might be true, or alternatively, because of a mistaken belief that they could not be true. . . . In our earlier work on immunological tolerance[11] . . . my colleagues R. E. Billingham and L. Brent and I completely missed the significance of observations which, rightly construed, would have led us to recognize an altogether new variant of the immunological response (the "graft against host" reaction) which now plays a very important part in the theory of tissue transplantation. The "facts" were before us, and if induction really worked we should not have been obliged to wait several years for their elucidation, which was hit upon independently by M. Simonsen and by Billingham and Brent themselves. . . .

There are numerous historic examples of preconceptions that have put a brake on research and led it down blind alleys. Not even the greatest scientists and the most acute observers are immune from the snares of preconceptions. As detailed by Rocky Kolb in *Blind Watchers of the Sky*, Galen, the famous Greek physician who lived in second-century Rome, was the undisputed authority in the sphere of human anatomy from antiquity up to the time of the Renaissance—a kind of Ptolemy of anatomy. Galen discovered numerous fundamental phenomena of human physiology and took important steps toward the understanding of the cardiac circulatory system. His treatise *De usu partium* remained the most authoritative and indisputable text for anatomy for more than a millennium. But in his description of the heart, for some reason Galen erroneously reported that the interventricular septum was permeated by a large quantity of minuscule pores, hardly perceptible to the human eye, through which some of the blood could permeate from the left ventricle to the right ventricle. Thirteen centuries later, we find one of the most formidable and uncompromising observers of nature that humankind has known, Leonardo da Vinci, coming to grips with the anatomy of the human heart. His ink drawings of the cardiac muscle are by far the most complete and detailed of his age. But when he tried to represent the central parts of the heart, Leonardo, who of course knew Galen's texts, covered the interventricular septum with a large number of small pores, of the kind that Galen had believed he saw many centuries previously. Very probably Leonardo, known for his explicit and disdainful rejection of all principles of authority in research, did not depict Galen's conclusions uncritically in his drawings. The episode is very interesting: evidently Leonardo, observing the heart, thought that he saw in the interventricular septum pores that in reality were not there.

In other cases there is a real philosophical or religious prejudice on the part of the scientist that emerges as a complicating factor in taking account of what the observations indicate and in interpreting experimental data. For example, this observation by Hubert Reeves on how little attention was paid for long decades to what today is considered the standard cosmological scenario is interesting. Certainly today we have much evidence at our disposal, but the long absence of attempts at experimental verification of the existence of the basis of low-temperature cosmic microwave background radiation remains curious, though it was within the scope of the technology of the 1950s.

Hubert Reeves[12]

The existence of [cosmic microwave background] radiation had been predicted thirty years before Penzias and Wilson's discovery by a brilliant astrophysicist named George Gamow. . . .

. . . Yet it was only by chance that Penzias and Wilson discovered the fossil glow thirty years after its existence had been postulated. Why was Gamow's prediction forgotten? During these years the theory of universal expansion was simply not viewed with favor. When I was a student at Cornell University, around 1960, no one ever spoke of it, and certainly no one thought of testing it. It just smelled bad. Was this because of its biblical overtones? I do not know.

The circumstances that led Einstein to force the cosmological solutions of his general relativity to make them compatible with a static universe, the only one that the great scientist thought credible, are well known. He had a preconception that prevented him from making the most sensational theoretical prediction in the history of science, the prediction that our universe is a historical reality, in evolution. The preconception here is the source of complications not so much of an experiment or observation but rather of the interpretation of a theoretical result. It is interesting to revisit these events at the beginning of the past century through the account of a direct witness such as Robert Jastrow.

Robert Jastrow[13]

Einstein had failed to notice that his theory predicted an expanding Universe. Later, it turned out that Einstein had missed still another expanding Universe solution to his own equations. This time the discovery was made by a Russian mathematician, Alexander Friedmann. He found that Einstein had made a schoolboy error in algebra which caused him to overlook the additional solutions. In effect, Einstein had divided by zero at one point in his calculations. This is a no-no in mathematics. As soon as Friedmann corrected the error, the missing solution popped out.

As an aside, Einstein seems to have been quite put out by Friedmann's discovery of his mistake, because in a rare display of discourtesy he ignored Friedmann's letter describing the new solution; and then, when Friedmann published his results in the *Zeitschrift für Physik* in 1922, Einstein wrote a short note to the

Zeitschrift calling Friedmann's result "suspicious," and proving that Friedmann was wrong. In fact, Einstein's proof was wrong.

Friedmann wrote Einstein shortly after Einstein's note appeared in the *Zeitschrift*, timidly pointing out that the master must have made another mistake. Friedmann was very respectful in his letter to the world-famous scientist, and clearly reluctant to challenge him. Every young person who has quarreled with his senior professor, at great peril to his job, knows the terror that must have been in Friedmann's heart when he wrote, after correcting Einstein's algebra, "Most honored professor, do not hesitate to let me know whether the calculations presented in this letter are correct." But Friedmann clearly felt that he had discovered something of great importance, and this must have given him courage, for then he went on, mindful of Einstein's initial silence, "I particularly ask you not to delay your answer to this letter," and finally, showing his teeth, "In the case that you find my calculations to be correct, . . . you will perhaps submit a correction."

Finally, Einstein acknowledged his double error in a letter to the *Zeitschrift* in 1923, in which he wrote, "My objection [to the Friedmann letter] rested on an error in calculation. I consider Mr Friedmann's results to be correct and illuminating." Einstein had accepted the legitimacy of his own brainchild.

Getting back to de Sitter, his theoretical prediction of an expanding Universe made a great impression on some astronomers immediately after World War I. For the first time, they saw the larger significance in Slipher's discovery of the outward-moving galaxies. Arthur Eddington, the English astronomer, picked up de Sitter's work and made a big to-do over it. Hubble said later that it was mainly de Sitter's result that had influenced him to take up the study of moving galaxies where Slipher had left off.

Around this time, signs of irritation began to appear among the scientists. Einstein was the first to complain. He was disturbed by the idea of a Universe that blows up because it implied that the world had a beginning. In a letter to de Sitter—discovered in a box of old records in Leiden some years ago—Einstein wrote, "This circumstance [of an expanding Universe] irritates me," and in another letter about the expanding Universe, "To admit such possibilities seems senseless."

This is curiously emotional language for a discussion of some mathematical formulas. I suppose that the idea of a beginning in time annoyed Einstein because of its theological implications. We know he had well-defined feelings about God, but not as the Creator or the Prime Mover. For Einstein, the existence of God was proven by the laws of nature; that is, the fact that there was order in the Universe and man could discover it. When Einstein came to New York in 1921 a rabbi sent him a telegram asking, "Do you believe in God?" and Einstein replied, "I believe in Spinoza's God, who reveals himself in the orderly harmony of what exists." ✺

As is well known, it was then Edwin Hubble who carried out the observations that led definitely to the evidence of cosmic expansion. But beyond doubt this fact was a source of disturbance and discomfort for many scientists.

Arthur Eddington[14]

The unanimity with which the galaxies are running away looks almost as though they had a pointed aversion to us. We wonder why we should be shunned as though our system were a plague spot in the universe. . . . These observational results are in some ways so disturbing that there is a natural hesitation in accepting them at their face value. But they have not come upon us like a bolt from the blue, since theorists for the last fifteen years have been half expecting that a study of the most remote objects of the universe might yield a rather sensational development. . . . This [the extraordinary rapidity of the expansion of the universe] is a rude awakening from our dream of leisured evolution through billions of years.

Such a conclusion is not to be accepted lightly; and those who have cast about for some other interpretation of what seems to have been observed have displayed no more than a proper caution. If the apparent recession of the spiral nebulae is treated as an isolated discovery it is too slender a thread on which to hang far-reaching conclusions; we can only state the bare results of observation, contemplate without much conviction the amazing possibility they suggest, and await further information on the subject. ✺

Observation requires that every relevant factor should be considered, without neglecting any of them. One possible effect of the preconception lies in "not seeing," more or less voluntarily, aspects that present themselves to our attention. As the Nobel Prize–winner for medicine Alexis Carrel says in the following passage, the temptation is to "suppress a part of reality from the inventory," simply because we are not in a position to understand it by the methods that we possess and think credible. On a larger scale, this mode of preconception applies to the claim of not considering real or worthy of attention and knowledge everything that science cannot deal with or dominate.

Alexis Carrel[15]

Another mistake consists in suppressing a part of reality from the inventory. There are many reasons accounting for this. We prefer to study systems that can easily be isolated and approached by simple methods. We generally neglect the more complex. Our mind has a partiality for precise and definitive solutions and for the resulting intellectual security. We have an almost irresistible tendency to select the subjects of our investigations for their technical facility and clearness rather than for their importance. Thus, modern physiologists principally concern themselves with physicochemical phenomena taking place in living animals, and pay less attention to physiological and functional processes. The same thing happens with physicians when they specialize in subjects whose techniques are easy and already known, rather than in degenerative diseases, neuroses, and psychoses, whose study would require the use of imagination and the creation of new methods. Everyone realizes, however, that the discovery of some of the laws of the organization of living matter would be more important than, for example, that of the rhythm of the cilia of tracheal cells. Without any doubt, it would be much more useful to free humanity from cancer, tuberculosis, arteriosclerosis, syphilis, and the innumerable misfortunes caused by nervous and mental diseases, than to engross oneself in the minute study of physicochemical phenomena of secondary importance manifesting themselves in the course of diseases. On account of technical difficulties, certain matters are banished from the field of scientific research, and refused the right of making themselves known.

Important facts may be completely ignored. Our mind has a natural tendency to reject the things that do not fit into the frame of the scientific or philosophical beliefs of our time. After all, scientists are only men. They are saturated with the prejudices of their environment and of their epoch. They willingly believe that facts that cannot be explained by current theories do not exist. During the period when physiology was identified with physical chemistry, the period of Jacques Loeb and of Bayliss, the study of mental functions was neglected. No one was interested in psychology and in mind disorders. At the present time, scientists who are concerned solely in the physical, chemical, and physicochemical aspects of physiological processes still look upon telepathy and other metapsychical phenomena as illusions. Evident facts having an unorthodox appearance are suppressed. By reason of these difficulties, the inventory of the things which could lead us to a better understanding of the human being has been left incomplete. We must, then, go back to a naïve observation of ourselves in all our aspects, reject nothing, and describe simply what we see. ✺

Observation and Realism: Observing Is Less Easy than Reasoning

The way to knowledge requires a position of realism in which observation coincides with an openness to the real, consciously giving priority to the datum as it emerges. As Luigi Giussani notes, "Realism is the urgent necessity not to give a more important role to a scheme already in our minds, but rather to cultivate an entire, passionate, insistent ability to observe the real event, the fact."[16] The prevalence of observation over reason, which is called for in this other passage from Alexis Carrel, is certainly not intended to diminish the value of the logical capacity of reason; however, it tries to take account of the fact that every moment of knowledge requires a tenacious attachment to the datum observed in its entirety.

Moreover, continually to submit one's own partial interpretation to the real data involves labor, a sacrifice.

Alexis Carrel[17]

In the soothing softness of the modern world, the mass of traditional rules which gave consistency to life broke up. . . . Thanks to the progress of technology, the greater part of the restraints imposed on us by the cosmos have disappeared and, along with them, the creative personal effort. . . . The frontiers of good and evil have vanished. . . . Everywhere division reigns. . . .

. . . Instead of advancing toward concrete reality, we have stuck fast in abstractions. Undoubtedly, concrete reality is difficult to grasp and our minds are glad to take the line of least resistance. Perhaps it is man's natural sloth which makes him choose the simplicity of the abstract rather than the complexity of the concrete. It is less arduous to hymn the praises of formulas or to drowse over principles than to find out laboriously how things are made and by what means they can be manipulated. It is easier to argue than to observe. As everyone knows, few observations and much discussion are conducive to error: much observation and little discussion to truth. But there are far more minds capable of constructing syllogisms than of accurately grasping the concrete.

"Attending to the facts" is the methodological criterion stated by a great observer such as Charles Darwin: "I must begin from a good factual basis and not from a principle, which is always suspect of being wrong." An experimental physicist, Michael Faraday, states that openly in a letter to André M. Ampère.

Michael Faraday[18]

Sir,

. . . I am unfortunate in a want of mathematical knowledge and the power of entering with facility into abstract reasoning. . . . I am obliged to feel my way by facts closely placed together so that it often happens I am left behind in the progress of a branch of science not merely from the want of attention but from the incapability I lay under of following it notwithstanding all my exertions. It is just now so I am ashamed to say with your refined researches on electro-magnetism or electrodynamics. . . . On reading your papers and letters I have no difficulty in following the reasoning but still at last I seem to want something more on which to steady the conclusions. . . . I fancy the habit I got into of attending too closely to experiment has somewhat fettered my powers of reasoning and chains me down and I cannot help now and then comparing myself to a timid ignorant navigator who though he might boldly and safely steer across a bay or an ocean by the aid of a compass which in its action and principles is infallible is afraid to leave sight of the shore because he understands not the power of the instrument that is to guide him. With regard to electro-magnetism also feeling my insufficiency to reason as you do I am afraid to receive at once the conclusions you come to (though I am strongly tempted by their simplicity & beauty to adopt them) and more so because I have seen the judgements of such men as Berzelius Prechtel &c &c stumble over this subject. Both these philosophers I believe and others also have given theories of electro-magnetism which they stated would account not only for known facts but even serve to predict such as were not then known and yet when new facts came (rotation for instance) the theories fell to pieces before them. . . . These instances are sufficient to warn such feeble spirits as myself and will serve as my apology to you for not at once adopting your conclusions. . . . I delay not because I think them hasty or erroneous but because I want some facts to help me on.

I cannot help thinking there is an immense mine of experimental matter ready to be opened and such matter as would at once carry conviction of the truth with it. I do not think I shall have to wait long for it though I have no idea where it should come from except from you. . . .

. . . your obliged and humble
Correspondent and Servant
Michael Faraday ✺

"Realism," in the sense of a prevalence of observation of the facts over preconstituted schemes, does not relate only to experimental researchers; it is part of the method with which in fact all scientists work in their sphere. Here, for example, a realistic view emerges from the work of two great theoretical physicists, Albert Einstein and Paul Dirac.

Albert Einstein[19]

Turning to the theory of relativity itself, I am anxious to draw attention to the fact that this theory is not speculative in origin; it owes its invention entirely to the desire to make physical theory fit observed fact as well as possible. We have here no revolutionary act but the natural continuation of a line that can be traced through centuries. The abandonment of a certain concept connected with space, time and motion hitherto treated as fundamentals must not be regarded as arbitrary, but only as conditioned by observed facts.

The law of the constant velocity of light in empty space, which has been confirmed by the development of electro-dynamics and optics, and the equal legitimacy of all inertial systems (special principle of relativity), which was proved in a particularly incisive manner by Michelson's famous experiment, between them made it necessary, to begin with, that the concept of time should be made relative, each inertial system being given its own special time. As this notion was developed it became clear that the connection between immediate experience on one side and co-ordinates and time on the other had hitherto not been thought out with sufficient precision. The fundamental principle here is that the justification for a physical concept lies exclusively in its clear and unambiguous relation to facts that can be experienced. ✺

Paul Dirac[20]

In 1928, Paul Dirac published what was probably the crowning achievement of his immensely fruitful career: the Dirac equation of the electron. He had been led to the discovery by the need to reconcile quantum theory with the special theory of relativity. The Dirac equation did this in a deep and satisfying way. It was a quite unexpected extra bonus, however, that it also explained a hitherto totally baffling aspect of the electron's behaviour, namely that its magnetic effects were twice as strong as one would have expected them to be. This property emerged in a perfectly natural, but unforeseeable, way from the equation. A few years later Dirac was led to the discovery of antimatter (that the electron has a "twin," the positron, with which it annihilates to give a burst of radiation) by the need to find a way of understanding the negative energy solutions of his equation. Such remarkable fertility is surely a sign that one is in contact with physical reality. Our grasp of that reality is verisimilitudinous rather than absolute. There are further small magnetic effects that for their explanation require the more elaborate theory of quantum electrodynamics, to which the Dirac equation of a single electron is only an approximation.

It is experiences like this that encourage scientists to take a realistic view of their achievements and so to claim that we are learning what the physical world is really like. There remains, however, the question of how we are to characterize the method of scientific inquiry that yields such satisfying knowledge. ✺

In mathematics, too, despite the purely abstract image that we often have, the object of knowledge has in some way the nature of a "datum" of reality ("mathematical reality") that the scientist has to "obey." In his way the mathematician confronts "facts" that are discovered and therefore observed. Godfrey Hardy certainly thinks this, and said so in his famous *A Mathematician's Apology*.

Godfrey Hardy[21]

I have often used the adjective "real," and as we use it commonly in conversation. I have spoken of "real mathematics" and "real mathematicians," as I might have spoken of "real poetry" or "real poets," and I shall continue to do so. But I shall also use the word "reality" and with two different connotations.

In the first place, I shall speak of "physical reality," and here again I shall be using the word in the ordinary sense. By physical reality I mean the material world, the world of day and night, earthquakes and eclipses, the world which physical science tries to describe.

I hardly suppose that, up to this point, any reader is likely to find trouble with my language, but now I am near to more difficult ground. For me, and I suppose for most mathematicians, there is another reality, which I will call "mathematical reality"; and there is no sort of agreement about the nature of mathematical reality among either mathematicians or philosophers. Some hold that it is "mental" and that in some sense we construct it, others that it is outside and independent of us. A man who could give a convincing account of mathematical reality would have solved very many of the most difficult problems of metaphysics. If he could include physical reality in his account, he would have solved them all.

I should not wish to argue any of these questions here even if I were competent to do so, but I will state my own position dogmatically in order to avoid minor misapprehensions. I believe that mathematical reality lies outside us, that our function is to discover or observe it, and that the theorems which we prove, and which we describe grandiloquently as our "creations," are simply our notes of our observations.

Observation and Question: The Right Question Explores a New Piece of the Unknown

We said at the beginning of this chapter that scientific observation requires a way of looking at reality charged with tension, with the question of meaning and the hope of unity between what is observed and the totality of the universe. In this sense reality is "interrogated" by the one who observes it. Without this "question" the answer is difficult to perceive or to disclose. C. S. Lewis has written that nature often makes itself evident in response to the questions that we put to it.

This is the normal, if not the only, way by which scientific knowledge advances. The boldness of a researcher is that of knowing how to put the right questions. When in a group of researchers it happens that after long and more or less confused discussions "the question" is finally put to the test, researchers feel a satisfaction analogous to that which accompanies a true discovery. The well-placed question has something of the inevitable about it and is a prelude to a new transition.

Fred Hoyle[22]

What we do not know is an ocean. . . . I cannot go farther, in part because beyond the light of our small knowledge, ignorance compounds itself—we do not know what we do not know. I think this is what Fred Hoyle had in mind when, at a conference where a speaker remarked that "there are questions we cannot answer," Hoyle whispered to the physicist Philip Morrison that in science the answers are not important, the questions are. The scientist who asks the right question reconnoiters a new patch of the unknown, and may, with luck, bring it within the constricted but expanding boundaries of the known. . . . To learn new ways of asking questions, therefore, is a powerful thing. Fortunately the recent history of science offers a tale concerning just that business of question-asking.

The capacity to see the real with the weight of a question, to perceive the real as a promise or possibility of unity and meaning, can be recognized as a distinctive level of the human.

Carl Sagan[23]

Human beings are, at least so far, an extraordinarily successful species, dominating the land, sea, and air of their native planet, and now, in at least a preliminary way, setting forth to other places. The secret of our success is surely our curiosity, our intelligence, our manipulative abilities, and our passion for exploration—qualities that have been extracted painfully through billions of years of biological evolution. It is in the nature of mankind and the corollary of our success to ask and answer questions, and the deeper the question the more characteristically human is the activity. Today we are finding that a host of issues, once the exclusive province of philosophy and theology, are slowly yielding to scientific inquiry, that most human of human inventions. The structure of matter, the nature of consciousness, the origin and fundamentals of life, the motions of continents, the intelligence of other animals, the possibility of life on other planets, the formation and destinies of worlds, are all becoming accessible to the mind of man. . . .

. . . If we can invent a source for the matter in the universe we immediately encounter the question of the origin of that source, and thereby come face to face with the standard problem of an infinite regression of causes. If we are trapped in a universe with only one set of physical laws, it is difficult to imagine experiments about which other categories of physical laws are possible. Much has been learned about cosmology recently; much will almost certainly be learned in the coming decade or two. But there is some comfort in the thought that we will never know everything. It would be a very dull universe for any intelligent being were everything of importance to be known. ✺

Research is a matter of putting increasingly stringent and precise questions until the time when someone finally finds the right question, the one that makes it possible to transform a simple detail into an indication that clarifies a hypothesis. This is the case with the discovery of the neutron. The facts were the same for the Curie-Joliots and for Chadwick, but the latter entered the laboratory with a more adequate question.

James Chadwick[24]

The first event was the discovery of the neutron. It had a complex and dramatic history. Unlike many other discoveries, such as the x-ray, which happened in one evening, the discovery of the neutron took two years. It even has an important prehistory. Rutherford had repeatedly thought of the possible existence of a neutral particle of protonic mass. He conceived it as a hydrogen atom in which the electron had fallen into the nucleus, neutralizing its charge. Rutherford's speculations on the behavior of such a hypothetical particle had been expressed in his Bakerian Lecture of 1920, which . . . kept alive the possible existence of such a particle in the minds of his pupils.

Walther Bothe . . . and his student H. Becker took the first step toward the actual discovery of the neutron in 1928 when they bombarded beryllium with polonium alpha particles. . . . Their aim was to confirm the disintegrations observed by Rutherford and to find out whether they were accompanied by the emission of high-energy gamma rays. Using electrical counting methods, they found a penetrating radiation, which they interpreted as gamma rays. They tried to measure their absorption coefficient in order to estimate their energy. They extended their observations to lithium and boron and concluded that the observed gamma rays had more energy than the incident alpha particles. This energy had to come from nuclear disintegration. The investigated lasted a couple of years. . . .

Around 1931 two new scientists of great importance enter the scene: Irène Curie and her husband, Frédéric Joliot. . . .

The Joliots decided to use their exceptionally strong polonium sample to study Bothe's penetrating radiation. On January 18, 1932, they reported a surprising observation of great import. The radiation was able to eject protons from a paraffin layer. They discovered this with an ionization chamber connected to an electrometer, but the result was so strange that they tried to confirm it immediately with a cloud chamber, and on February 22, they published the result of this second observation, confirming the ejection of protons. . . . Why was it so strange that Bothe's penetrating gamma rays should eject protons? The projection of a free particle by an impinging proton is a form of Compton effect well known for electrons. In the ordinary Compton effect, however, the recoiling electrons are light (mc^2 = 0.51 MeV) and recoil easily, but protons are 1,836 times heavier and do not recoil so easily. If one billiard ball hits another one, they easily recoil; but if an automobile is hit with a billiard ball, it will not be set in appreciable motion.

When Curie and Joliot tried to interpret their observations as a Compton effect, they made a most unlikely proposal in view of both: the energy that incident gamma rays should have had and the collision cross-section that had to be attributed to them. This cross-section was about 3 million times larger than expected with a simple extension of the calculation valid for the electron. James Chadwick . . . reported to Rutherford the Curie-Joliot publication of January 18, and when his Lordship heard of the proposed explanation, it seems he said with unusual vehemence, "I do not believe it." On reading the same paper, Ettore Majorana, a young physicist in Rome, with his special sarcastic spirit, said, "What fools. They have discovered the neutral proton and they do not recognize it." Chadwick at the Cavendish did more. He repeated the experiments, using polonium plus beryllium as a source, but he collided the emerging radiation not only with hydrogen, but also with helium and nitrogen. . . . By comparing the recoils, he could then prove that the radiation contained a neutral component of mass approximately equal to that of the proton. He called it neutron and published the result by sending a letter to *Nature* on February 17, 1932. Curie and Joliot had thus missed a great discovery.

One of the reasons for Chadwick's speed and success was that he was mentally prepared for the concept of the neutron. He had previously made several attempts to produce the neutron in strong discharges and by other methods. In a paper on the discovery of the neutron he says that "some of these experiments were quite wildly absurd." To his great credit, when the neutron was not present he did not detect it, and when it ultimately was there, he perceived it immediately, clearly, and convincingly. These are the marks of a great experimental physicist.

It is rumored that Rutherford insisted that the Nobel Prize for the discovery of the neutron should go to Chadwick, who fully deserved it. To somebody who remarked to Rutherford that the Joliots had also made an essential contribution, Rutherford is said to have answered, "For the neutron to Chadwick alone; the Joliots are so clever that they soon will deserve it for something else."

Observation and Experiment: Experimentum Solum Certificat in Talibus

The question put by the researcher to nature becomes explicit in experiment. What is an experiment? It is observation of the response of nature to a very precise question. "What are you made of?" "If I drop two bodies of different masses from the same height, in what order do they reach the ground?" Conceiving an experiment arises from the desire to observe the object under preferential conditions of observation that make it possible to isolate certain aspects that are considered important for the underlying hypothesis, like the Alpinist of whom we have spoken, when he moves from here to there to vary his observation point. Conceiving an experiment, therefore, has the same dynamic of arising from a question or, better, follows from being able to put a clear question.

For example, the Hubble space telescope can be seen as the "matrialization" of questions addressed by astrophysicists to the stars or galaxies, in the hope of receiving an answer from their observation. How were the stars formed? Are there planets within them? What is the nature of dark matter? How did the galaxies evolve in time? At what rate is the universe expanding? These are questions to which we were in a position to give a partial answer even before the Hubble space telescope, but with the new instrument they have been taken to an unprecedented depth. Each of these questions has in some degree determined the particular characteristics (the so-called scientific requirements) with which the instrument was conceived, designed, and built. The design of an instrument is literally dominated by the "questions" that the instrument is called on to put to the object on which it is focused. Researchers have thus invented instruments of various kinds, sometimes—especially in the past—simple and ingenious; at other times—increasingly frequently—so sophisticated and expensive that they require the continued efforts of hundreds of persons over decades.

It is possible to trace the dawn of the modern scientific attitude to the heart of medieval Europe, where awareness emerges of the importance of observation and experiment as a way of learning about the real. Albertus Magnus, for the Catholic Church the patron of scientists, embodies the rise of this attitude. It has been said of him by H. Stadler: "Albert was an observer of the first order, and if the development of the natural sciences had followed the way that he had taken it would have avoided a detour of thirty years."

Albertus Magnus[25]

The greatness of Albert as a naturalist is growing in the eyes of experts on the subject, the more they have dispassionately examined his ideas and his doctrines.

Certainly the successes of Roger Bacon are rightly celebrated in the precise natural sciences, but in the descriptive natural sciences Albert prevails. He was convinced that in the natural sciences one could get nowhere with generic theories and the technique of syllogism, and that in this field experiment and observation had to prevail. Experiment, observation, reasoning are for him legitimate instruments of positive science, reshaping the blind criterion of authority (*magister dixit*), for which that of things is to be substituted: *probata per experimentum*.

It is not that he wants to make a clean sheet of what the ancients had written about nature, but he recognizes that it is not possible for a single individual to subject the whole of nature to experience and that it is therefore necessary in part to trust the authority of his predecessors. But it is necessary for the student to know how to discern with a critical spirit which authors provide guarantees of reliability. Only those who assert things proved by experiment are to be trusted: *experimentum solum certificat in talibus.*

The open-air life of young Albert, a passionate hunter who rode through woods and mountains, was made to favor his natural inclination toward scientific research. This interest lasted all his life, so that he could collect a great mass of observations. No class of animals escapes his attentive gaze, from vertebrates to invertebrates, from mammals to fish, from birds to snakes. He shut himself in his cell for long hours to observe a spider artfully weaving its web and stretching it skillfully toward its prey. In the convent garden in Cologne he would sit for days beside a beehive or an anthill to study in minute detail the life of the industrious bees and the prudent ants. In Venice his attention was drawn to the strange figurations of a piece of marble and he examined the structure of the blocks. At Padua he was struck by the asphyxiating gas from a blocked well, the poisonous miasma of which had killed two workers, and investigated its causes.

Albert also used what we would today call laboratory experiments.

Thus he occupies a special place purely in the history of chemistry. He purified gold with calcination, separated it from silver by means of aqua fortis, and investigated the effects of the combination of sulphur with metal. Because of these experiments people in their legends made him an alchemist and a magician.

Finally, Albert has been recognized as a geographer: he revealed original ideas about the arguments used to demonstrate that the earth is round. To him we owe a descriptive cosmography which three centuries later served Christopher Columbus. Among the treasures preserved in the library of Seville one can still see a codex by Albertus Magnus, annotated by Christopher Columbus.

Experiment 3

To invent is truly to find. ALESSANDRO MANZONI

"Reasonable" denotes someone who subjects his own reason to experience. JEAN GUITTON

The scientist is not someone who shuts himself up hidden in a storeroom trying to think. MAX PERUTZ

IMPELLED BY ITS unstoppable desire for the truth, human reason is capable of following different yet complementary modes of knowledge. The methods of history, science, logic, philosophy, theology, and morality are all "paths" on which one can proceed toward different "types of goal." The method with which one can achieve a logical truth, for example, "A is different from not-A," requires a particular mental disposition toward the subtle interplay of inescapable and basic evidences of thought. With the historical method it is possible to arrive at a conclusion of the type "the independence of the United States was favored by . . ."; this method clearly requires a capacity to pay attention to the documents and testimonies given by other people and a predisposition to formulate interpretations keeping to the facts. However, it should be noted that these prevalent aspects are dimensions that are necessarily also present in all the other methods of knowledge. Historians certainly cannot do without logic in support of their work, and mathematicians cannot renounce completely a certain interpretative capacity, in the broad sense, of the evidence with which they are confronted.

But is it possible to identify a basic prerogative, if we may put it that way, of the scientific method? A very great deal has been written on the extraordinary and dramatic events that accompanied the self-assertion of experimental science in sixteenth-century Italy, and there is discussion of the appropriateness of calling the surprising, one might say almost moving, knowledge of nature among ancient Greeks such as Pythagoras or Aristarchus, "science"; less frequent is there awareness of the contradictory and extremely rich course that the scientific dimension of knowledge followed in the medieval period. But this is certainly not the place to discuss these themes in depth. What needs to be emphasized is simply that when the traces of the beginning of scientific thought and action are found in history, we must look to see what evidence there is of a precise methodological approach, generally accepted as the characteristic of science: the experimental method. When someone thinks up an experiment, we can begin to speak of scientific experience. The scientific method has experiment as its particular prerogative, and its strategy of verification as a source of innovation. What does this involve?

For scientists, experiment is the usual way of "experiencing" reality according to the particular type of cognitive question that motivates them. We might think, for example, of a Formula One driver: he has to take account of many important aspects, all vital. He must be in optimum physical and psychological condition, for which, for example, he will be required to undergo training in the gym. From time to time he will have to study the details of the layout of the course, decide tactics with various pit stops and tire changes, and that sort of thing. Moreover, he will have to know his vehicle very well, with all the subtleties of the engine and the aerodynamics; close collaborations with the mechanics and engineers of the team will be a great advantage. But above all, at a certain point, the driver will have to get in the car and drive. For him, this is the moment of direct experience, the apex of verification of the "experiment." The driver has to "prove" the machine. To do this, every time he drives on to the track after changes have been made, after the umpteenth discussion with his mechanics, he will be utterly intent in deriving the possible benefit (or not) from a slight modification in the aerodynamics of the rear spoiler, the way new tires hold the curves, the efficiency of the automatic gear change. Before any test circuit the driver will have raised a number of precise questions to which his manager must seek to respond.

Rather like the driver who has to "prove" his vehicle, to improve his race times, the scientist has to "prove" the object of his research to know it. And just as the driver gets into his vehicle with some key questions, so the researcher will seek to interrogate the phenomenon that he studies, not in a generic fashion but as sharply as possible, in such a way that it is possible to gain some clear and definitive answers. Researchers therefore continually try to think of "stratagems" to "force" nature to give clear answers. And they know that to hope for a clear reply, they must put the questions in the most simple and direct way (while seeking not to offend anyone!). So the use of our reason in thinking up an experiment has a certain analogy with the effort that we make in attempting to perfect the formulation of a question. The first task of the experimenter is to bring about the transition from a vague sense of curiosity, an indistinct image of what we would like to know of the object, to the identification of the precise, unambiguous, inevitable problem.

This is so inevitable that even a negative answer, and indeed a nonanswer, ends up by increasing knowledge.

Experiment and Nature: The Electrons Know Very Well How to Behave

An account by a protagonist confronts us with the trepidation with which the researcher "feels" his own experiment. Millikan describes, not without a sense of amazement and almost of gratitude, the experiment of the oil drop that he thought up in order to give a clear and definitive answer to the age-old question of the continuity or corpuscularity of electric charges and ultimately of matter. The experiment forces a piece of reality to show its distinctive feature, at least for a moment. It should be noted how Millikan explicitly identifies the fundamental success of his brilliant experiment not only in the (quite extraordinary) precision with which it was capable of measuring the charge of the electron, but rather in the "qualitative" demonstration of the discrete nature of the electric charge. This is a simple experiment—of the kind that is often proposed to students in first courses in laboratories of scientific faculties—and precisely for this reason is powerful and capable of posing the big question in an unequivocal way: a "direct, simple, and accurate" proof.

Robert Millikan[1]

From 1909, when I built my first apparatus with the oil drop, to the summer of 1912, I spent almost all my available time, apart from that reserved for lectures and helping the researches of graduate students, in working around oil drops.

It was fascinating to see with how much certainty one could count the precise number of electrons which installed themselves on a given drop, regardless of whether this was one electron or one hundred; in fact one needed only to move the drop up and down, and already, always measuring accurately the time and then calculating the minimum common multiple of quite a long series of velocities conferred by the field of the drop, according to which the electrons carried by the group were added or subtracted. *This series of velocities always changed in a series of unitary steps*; that is why it was necessary only to determine the number of these steps or leaps (for example from six to ten) of velocity to be certain of having found the step corresponding to the capture or loss of a certain electron.

The cases like those now treated, in which the drop is small and therefore falls slowly under the action of the force of gravity, are quite interesting, since then it is enough for a single electron to be captured by the drop, because this begins to leap with some velocity and it is enough for this to be lost for the drop immediately to change the direction of its movement and begin to rise. Then it can capture another electron and the drop begins with a spurt to leap again with its initial velocity.

The following episode shows how absorbed I was in these experiments during that period. It took a whole hour to calculate the data relating to a single drop. One evening my wife and I were entertaining guests to dinner. At six o'clock I was only halfway through the data relating to one particular drop. My wife then telephoned me to say that "I had been observing an ion for an hour and a half and had to stop work," and I asked her to begin dinner with the guests but without me. The guests were pleased at my interest in the house, since I had "washed and ironed for an hour and a half and had to finish the work" (which was the way in which they had understood "watched an ion for an hour and a half . . .").

Another episode shows how our little drops proved well suited to the research. When I had to stop work on a drop, I often balanced it with the field; once, having left the little drop as it were suspended in mid-air, I went to lunch and returned after an absence of more than an hour to find it in the same position in which I had left it.

It was illuminating to see how the movements of every oil drop of different weights (I was working with hundreds of drops of different weights) could be controlled, giving at will positive or negative electron charges to the drop with the help of X-rays or a little radium, or completely charging it when it was quite small and noting that in the absence of a field its velocity in falling was precisely the same as the charge with which it was charged. This indicated that when a little drop captured a charge and began to leap with the minimum possible velocity I could be certain that it had a single electron. All the apparatus was a device aimed at capturing a single electron and making it possible to see it transported by an oil drop. In this way we could work with a single electron on a drop, with two or three or a dozen or even a hundred electrons, and the "surges in velocity" produced by the constant field always proved either equal to the velocity conferred by the field when a single electron leaped on the drop, or precise multiples of this speed. In sum, we could effectively see the precise instant at which the electron leaped on the drop or left it.

In the autumn of 1910 I published my first reasonably complete article on "Isolation and measurement of the electron"; immediately after that I began to perfect the techniques, to correct Stokes's law and to reach the limits of possibility for an absolute value of the electron charge. It was long and tedious work which necessitated a whole group of ancillary researches, such as that into the viscosity of the air. I entrusted this to graduate students as subjects for their theses. In the spring of 1912 I had succeeded in collecting the necessary data for what I hoped could be the final and absolute determination of the numerical value of the charge of the electron. However, I never considered this determination as the main aim or most important result of the drop of oil method; in my view this method had to serve to conclude in a definitive way the violent polemic of the time on the atomic structure of matter and of electricity. I remember that the most direct, simple, and accurate proof not only of the corpuscular theory of electricity but also of the equation of Brownian movements was one which came outside the oil drop technique, according to the procedure initiated by Harvey Fletcher and me and developed with great skill and greater elaboration by Fletcher in his thesis.

I now have to leave this historical narrative for a moment to say something about the last phase of the polemic on atomic theory and the reversal of course which then took place in scientific thought, to show clearly the change that happened between 1904 and 1912. The Great Exposition at St. Louis took place in 1904, and on this occasion a scientific congress was held. A whole day of this congress was devoted to discussion of the fundamental problem whether an atomic theory or a particle theory was necessary to interpret the known observed facts, or whether a theory of continuity in respect of both electricity and matter would work equally well. Ostwald came from Leipzig to defend the second alternative, while Van't Hoff came from Berlin to argue for the first. Boltzmann came from Vienna to support Van't Hoff. Now it seemed very strange to us at that time that one could discuss such a question and that distinguished men such as Ostwald and Helms and indeed the brilliant philosopher Ernst Mach could then defend the continuity theory. In 1912 this state of affairs was changed and Ostwald, who for years had been the standard-bearer of the continuity school, was honest enough to write the following words in the introduction to the 1912 edition of his *General Chemistry*:

"I am now convinced that in recent times we have gained possession of the experimental proof that matter has a discontinuous or granular constitution, researched in vain by the supporters of the atomic hypothesis for hundreds and thousands of years. On the one hand the isolation and calculation of the gas ions . . . and on the other the concordance of the Brownian movements with what is required by the kinetic hypothesis . . . now authorize the most prudent scientist to say that there is proof of the atomic theory of matter. The atomic hypothesis is thus elevated to the position of a well-founded scientific theory."

Such polemic brings out one of the reasons why the drop of oil experiment attracted so much attention throughout the world in 1910, in 1911, and before it was used to determine the absolute value of the electron charge. However, at this time it was energetically being argued that the electron charge was only a statistical means; these people thought that they had found experimental proof of the existence of smaller charges than that attributed to the electron functioning as charges of some colloidal particles. But these researchers too established, as I did, that using a given particle and noting the change in its velocity due to successive captures of ions, it could be stated that all the velocities that the particle could assume in a certain electrical field were always precise multiples of a minimum velocity conferred by the field. This was in clear contrast to the claim that the electron was divisible. The important thing was *the series of values which were precise multiples* of a certain value and *not the absolute value* of the charge, so that in some experiments, this last value could prove, and in fact proved, to be wrong. I have checked and explained elsewhere the reasons for these errors; this check has also been made by others.

In this one-page confession, the theoretical physicist and mathematician Freeman Dyson, getting to grips with Millikan's experiment, relates with irony the episode in which he was definitively convinced of his own ineptitude for experimental physics. But his mistake was the occasion for an unexpected deeper and more dramatic perception of the "real" existence of those small particles with electrical charges called electrons present in the setup of the laboratory experiment as in every corner of the world and of the inexplicable mystery of the "obedience" of these particles to the laws of nature that his equations in theoretical physics sought to express. It is a trace of that obedience that in various ways every experiment tries to prove.

Freeman Dyson[2]

As a relaxation from quantum electrodynamics, I was encouraged to spend a few hours a week in the student laboratory doing experiments. These were not real research experiments. We were just going through the motions, repeating famous old experiments, knowing beforehand what the answers ought to be. The other students grumbled at having to waste their time doing Mickey Mouse experiments. But I found the experiments fascinating. In all my time in England I had never been let loose in a laboratory. All these strange objects that I had read about, crystals and magnets and prisms and spectroscopes, were actually there and could be touched and handled. It seemed like a miracle when I measured the electric voltage produced by light of various colors falling on a metal surface and found that Einstein's law of the photoelectric effect is really true. Unfortunately I came to grief on the Millikan oil drop experiment. Millikan was a great physicist at the University of Chicago who first measured the electric charge of individual electrons. He made a mist of tiny drops of oil and watched them float around under his microscope while he pulled and pushed them with strong electric fields. The drops were so small that some of them carried a net electric charge of only one or two electrons. I had my oil drops floating nicely, and then I grabbed hold of the wrong knob to adjust the electric field. They found me stretched out on the floor, and that finished my career as an experimenter.

I never regretted my brief and almost fatal exposure to experiments. This experience brought home to me as nothing else could the truth of Einstein's remark, "One may say the eternal mystery of the world is its comprehensibility." Here was I sitting at my desk for weeks on end, doing the most elaborate and sophisticated calculations to figure out how an electron should behave. And here was the electron on my little oil drop, knowing quite well how to behave without waiting for the result of my calculation. How could one seriously believe that the electron really cared about my calculation, one way or the other? And yet the experiments at Columbia showed that it did care. Somehow or other, all this complicated mathematics that I was scribbling established rules that the electron on the oil drop was bound to follow. We know that this is so. Why it is so, why the electron pays attention to our mathematics, is a mystery that even Einstein could not fathom. ✺

We already emphasized in chapter 1 that belief in the existence of an objective reality outside us is essential for setting research in motion. Experimentation is the action with which the human subject in some way "goes in search" of the relationship with such objective reality. In the experiment it is important to isolate as far as possible the piece of reality that we are interrogating and to make the phenomenon as far as possible speak detached from influences that the presence of the experimenter himself can introduce. As is well known, the advent of quantum mechanics from the beginning of the twentieth century has led to a profound revision of the relationship between subject and object, bringing out the impossibility of an absolute independence of spectator and phenomenon. It is no coincidence that Erwin Schrödinger felt this problem in a dramatic way.

Erwin Schrödinger[3]

Without being aware of it, we exclude the subject of knowledge from the sphere of nature that we try to get to know. However, here we play the role of a spectator who does not belong to the world, through whom this process becomes an objective world. . . . We have achieved a moderately satisfactory image of this world, paying the ultimate price to draw it outside the image itself, retreating to the role of indifferent observers. ✺

To seek a "distance" between subject and object does not mean introducing an extraneous or indifferent element. Indeed it appears that the "indirect step" that the subject has to make in order not to spoil his possibility of knowing the phenomenon is necessary in order to achieve a more profound unity with the object: the knowledge of the phenomenon on the part of the subject. Moreover the detachment, the "indirect step" in respect of the object, is in an analogous way required in other forms of knowledge: even to admire a picture[4] it is necessary to stand a certain distance from it.

The attraction for a particular object, a condition that determines the cognitive experience, must not lead one astray into a form of myopia that prevents one gaining a global view of the phenomenon being studied. It is only here that the particulars find their right position. Indeed sometimes it is this same unitary vision that leads to the discovery of features that are at first hidden: in short, it may happen that the eagerness to understand all the details can hide the decisive indication. Michael Polanyi describes this in relating his first experiences of research into crystallography.

Michael Polanyi[5]

The strength of solids had now become my principal interest. The technological purpose of the Institute had thrown this great problem into my lap. I saw that the characteristic feature of the solid state, namely its solidity, was yet unexplained and, indeed, hardly explored by physicists. I found that in the light of the recently discovered structure of rock salt, such a crystal should be thousands of times stronger in resisting rigid rupture or plastic deformation than it actually was. . . . So I set out to show experimentally that crystals shorter than a few millimeters were stronger than those of greater length. The result was inconclusive, and the whole idea may have been wrong; but in pursuing it I stumbled on an important aspect of the strength of materials which seemed to reflect my original paradox and to encourage the way I was trying to solve it: I came to know about the hardening of materials by cold working.

I was deeply struck by the fact that every process that destroyed the ideal structure of crystals (and thus reduced the areas which could be regarded as single molecules) increased the resistance of crystalline materials. This seemed to confirm the principle by which I explained the low resistance of crystals to stress and to refute the rival theory—inspired by the work of Griffiths on quartz threads—that the weakness of crystals was due to cracks or other imperfections of structure. The cold working of rock salt crystals by vigorously scraping their sides and of tungsten crystals (obtained from filaments for incandescent lamps) by drawing them through a nozzle confirmed this. . . .

I shall pass by our inquiries starting from the discovery of fibre structure in cold worked polycrystalline metals, by merely mentioning that it was nice to be able to account for this phenomenon by the crystallography of plastic deformation as observed in single crystals. More interesting, perhaps, was the fact (found with P. Beck) that the annealing of a bent aluminum crystal caused it to recrystallize, while, if it were straightened out before annealing, no recrystallization took place. These were sidelines, for they threw no light on the nature of solid strength, which remained shrouded in the paradox that all effects which would tend to restore the ideal crystal structure appeared to weaken the material far below its ideal strength, whereas every disturbance of this structure tended to raise its strength towards its ideal value.

My fascination with this fact had borne fruit—but it proved excessive. From a paper written by Erich Schmid on the occasion of my seventieth birthday, I gather that the picture I had formed of the hardening and weakening of crystals made me overlook an important clue for modifying it. My experiments with W. Ewald (1924) show that bending a rock salt crystal in one direction hardens it only for further bending in the same direction and actually weakens it for bending it back. Schmid says that such mechanical recovery has subsequently been effected in various crystals, including those of metals. Had I noticed the fact that deformation may actually weaken a crystal, my mind would have been more hospitable to the idea that the extremely low resistance of crystals against plastic deformation might be due to the kind of irregularity in the structure of the crystals that is now known as dislocation. ✺

Experiment and Method: Fact Is the Most Stubborn Thing in the World

Sometimes an experiment aims to show how a phenomenon can be—or possibly cannot be—explained within a certain order described by known laws. At other times, more rarely, instruments with new levels of sensitivity appear (even thanks to an unexpected technological advance) and the experiment is launched in the hope of finding something new and interesting: just as a fisherman who finds a means of lowering his nets to greater depths. As the naturalist René J. Dubos has written, "The experiment serves two purposes, often independent one from the other: it allows the observation of new facts, hitherto either unsuspected, or not yet well defined; and it determines whether a working hypothesis fits the world of observable facts."[6]

In both cases the inevitable and continual submission of the theory to experiment, of thought to reality, lies at the very heart of the mentality and method of the scientist. And when reality contradicts the hypothesis, the latter is discarded, set aside; at least for the moment it has to be removed (possibly it can be put in quarantine in the expectation of new developments in observation that are always possible). But it is important to go along with the response of reality, to follow promptly the signals of its indications, as Claude Bernard warns: "Our ideas are only intellectual instruments that help us to penetrate phenomena. It is necessary to change them when they have fulfilled their role—as one changes a bistouri when it has served long enough."[7]

Murray Gell-Mann[8]

In practice, the scientific enterprise does not precisely conform to any clearcut model of how it ought to work. Ideally scientists perform experiments either in an exploratory mode or in order to test serious theoretical proposals. They are supposed to judge a theory by how accurate, general, and coherent a description it gives of the data. They should not exhibit such traits as selfishness, dishonesty, or prejudice.

But the practitioners of science are, after all, human beings. They are not immune to the normal influences of egotism, economic self-interest, fashion, wishful thinking, and laziness. A scientist may try to steal credit, knowingly initiate a worthless project for gain, or take a conventional idea for granted instead of looking for a better explanation. From time to time scientists even fudge their results, breaking one of the most serious taboos of their profession.

Nevertheless, the occasional philosopher, historian, or sociologist of science who seizes upon these lapses from scientific rectitude or ideal scientific practice in order to condemn the whole enterprise as corrupt has failed to understand the point of science. The scientific enterprise is, by its nature, self-correcting and tends to rise above whatever abuses occur. Extravagant and baseless claims like those made for polywater or cold fusion are soon discounted. Hoaxes like the Piltdown man are eventually exposed. Prejudices such as those against the theory of relativity are overcome.

A student of complex adaptive systems would say that in the scientific enterprise the selection pressures that characterize science are accompanied by the familiar selection pressures that generally occur in human affairs. But the characteristically scientific selection pressures play the crucial role in advancing the understanding of nature. Repeated observations and calculations (and comparisons between them) tend to weed out, especially in the long run, imperfections (that is, features that are imperfect from the scientific viewpoint) introduced by the other pressures.

While the historical details of any scientific discovery are usually somewhat messy, the net result can sometimes be a brilliant and general clarification, as in the formulation and verification of a unifying theory.

In the subjection of theory to the experimental datum, the key lies in the capacity of science to keep going, to maintain a certain at least long-term internal coherence, to succeed in time in liberating itself—even laboriously but inexorably——from falsehood and blatant oversights. As Mikhail Bulgakov observed, "Fact is the most stubborn thing in the world";[9] the tribunal of the real world sooner or later calls in question our models and our theories.

Murray Gell-Mann[10]

The concept of the complex adaptive system is beautifully illustrated by the human scientific enterprise. The schemata are theories, and what takes place in the real world is the confrontation between theory and observation. New theories have to compete with existing ones, partly on the basis of coherence and generality, but ultimately according to whether they explain existing observations and correctly predict new ones. Each theory is a highly condensed description of a whole class of situations and, as such, needs to be supplemented with the details of one or more situations in order to make specific predictions.

The role of theory in science should be fairly obvious, and yet in my own case it took me a long time to get a real feeling for it, even though I was to devote my whole career to theoretical science. It was only when I entered graduate school at MIT that it finally dawned on me how theoretical physics works.

As an undergraduate at Yale, I had managed to get high grades in science and math courses without always understanding the point of what I was learning. Sometimes, it seemed, I was able to get by merely by regurgitating on examinations what I had been fed in class. My views changed when I attended one of the sessions of the Harvard–MIT theoretical seminar. I had thought of the seminar as some sort of glorified class. In fact, it was not a class at all, but a serious discussion group on subjects in theoretical physics, particularly the physics of atomic nuclei and elementary particles. Professors, post-docs, and graduate students from both institutions attended; one theorist would lecture and then there would be a general discussion of the topic he had presented. I was unable to appreciate such scientific activity properly because my way of thinking was still circumscribed by notions of classes and grades and pleasing the teacher.

The speaker on this occasion was a Harvard graduate student who had just completed his PhD dissertation on the character of the lowest energy state of a nucleus called boron ten (B^{10}), composed of five protons and five neutrons. By an approximation method that seemed promising but was not guaranteed to work, he had found that the lowest state should have a "spin" angular momentum of one quantum unit, as was generally believed to be the case. When he finished his talk, I wondered what kind of impression his approximate derivation of the expected result had made on the distinguished theoreticians in the front row. The first person to comment was not a theoretician at all, however, but a little man with a three days' growth of beard who looked as if he had just crawled out of the basement of MIT. He said, "Hey, da spin ain't one. It's t'ree. Dey measured it!" Suddenly, I understood the main function of the theoretician: not to impress the professors in the front row but to agree with observation. (Of course, experimentalists can make mistakes; in this case, however, the observation to which the scruffy man referred turned out to be correct.)

I was ashamed of not having been fully aware earlier that the scientific enterprise worked that way. The process by which theories are selected according to their agreement with observation (as well as their coherence and generality) is not so different from biological evolution, where genetic patterns are selected according to whether they tend to lead to organisms that have progeny. But I was not to appreciate fully the parallel between the two processes until many years later, when I had learned more about simplicity and complexity and about complex adaptive systems.

Theories typically arise as a result of a multitude of observations, in the course of which a deliberate effort is made to sort out the wheat from the chaff, to separate out rules from special or accidental circumstances. A theory is formulated as a simple principle or set of principles, expressed in a comparatively short message. As Stephen Wolfram has emphasized, it is a compressed package of information, applicable to many cases. There are, in general, competing theories, each of which shares these characteristics. To make predictions about a particular case, each theory must be unfolded or re-expanded; that is, the compressed general statement that constitutes the theory must be supplemented with detailed information about the special case. The theories may then be tested by further observations, often made in the course of experiments. How well each theory does, in competition with the others, at predicting the results of those observations helps to determine whether it survives. Theories in serious disagreement with the outcome of careful and well-designed experiments (especially experiments that have been repeated with consistent results) tend to be displaced by better ones, while theories that successfully predict and explain observations tend to be accepted and used as a basis for further theorizing (that is, as long as they are not themselves challenged by later observations).

. . . The possibility of failure of an idea is always present, lending an air of suspense to all scientific activity.

Sometimes the delay in confirming or disproving a theory is so long that its proponent dies before the fate of his or her idea is known. Those of us working in fundamental physics during the last few decades have been fortunate in seeing our theoretical ideas tested during our lifetimes. The thrill of knowing that one's prediction has actually been verified and that the underlying new scheme is basically correct may be difficult to convey but it is overwhelming.

The experimental approach turns out to be the adequate method for the knowledge of that particular "object" that is natural reality and the order that governs it. The centrality of the experiment in scientific method is like an insurmountable wall that opposes scientists' inevitable tendency to project their own ideas on reality. Thus, the development of scientific experience in history has been helped by those who, more than others, have had the gift of a natural, almost instinctive, clarity and certainty of method. This is demonstrated by three figures in experimental biology from different periods: Spallanzani, Bernard, and Darwin.

Lazzaro Spallanzani[11]

In all the fields in which Spallanzani was involved he succeeded in discovering important truths. Without doubt he lived in an age in which, since techniques were relatively rudimentary and nature was still full of mysteries, making discoveries was less difficult than in our day. Every living being was so to speak a receptacle of wonders: to be amazed biologists had only to dissect a polyp, decapitate a mollusk, breed an aphid in isolation. But the splendid success of abbot Spallanzani cannot be explained solely by invoking the circumstances. He was an incomparable observer of rare ability, which is all the more surprising when one thinks that basically he was self-taught.

He is great not only because of his discoveries but also because of the method with which he succeeded in making them. He was not the first to experiment on living beings; Harvey, Haller, and Réaumur had done so before him. However, he was one of the first, if not the first, to subject complex problems to a close experimental analysis, that is, to break them up, to reduce them to far simpler problems, or try to resolve them one by one with a series of logically connected experiments.

In some cases . . . Spallanzani did not avoid the despotism of the preconceived idea. But for the most part he confronted problems with a complete freedom of spirit without taking account of what had been said or thought by his predecessors, however distinguished they may have been, without becoming preoccupied with the question whether or not his conclusions agreed with the notions that had now been arrived at.

Almost always he tried to go back to the facts, which are the only true source of opinions: "The unchangeable nature of my method," he says, "even in what is most universally embraced but depends on facts, is to leave aside the authority, however respectable, of those who have established them, while learning from a practical examination of these same facts."

A passionate experimenter, Spallanzani did not stop when confronted with work and did not hesitate to multiply, reproduce, and vary his experiments, "even when he was certain that his observations were correct and could believe that they had been done well" (Senebier). Hunter . . . accused him of having made too many, a criticism which certainly would not be made in our day.

Spallanzani gladly attempted experiments which at first sight might seem superfluous, either because their success appeared too certain or because they seemed impossible: in fact he knew that it was possible to err in one way or another, since it is impossible to outguess nature and one can never sufficiently distrust what one thinks that one knows.

When confronted with a problem Spallanzani examined it from every side, under every aspect: he continually varied the conditions of the experiment, experimented "in series" with the largest possible number of animals in order to eliminate particular, accidental, individual factors.

"He never abandoned without regret the subjects he had studied most often because he was always afraid of not having dissected them sufficiently" (Senebier).

Spallanzani confessed that when he studied some subject by means of experiments he used to do so in every sense, even those which seemed to take him further from his original aim.

He thought this particular way of interrogating nature fruitful: "I have no doubt that one of the most effective means of promoting physical science is to take a new course, or continue the journey made by others, beginning where they have ended. But such experience as I flatter myself in having in experimental matters has shown me that rather than taking a direct route, as most people do, it is sometimes more fruitful to go sideways and take steps which others have not only never taken but which have never occurred to them."

Claude Bernard[12]

Claude Bernard considered that one should observe an experiment with an open mind for fear that if we look only for one feature expected in view of a preconceived idea we will miss other things. This, he said, is one of the greatest stumbling blocks of the experimental method, because, by failing to note what has not been foreseen, a misleading observation may be made. "Put off your imagination," he said, "as you take off your overcoat when you enter the laboratory."

Charles Darwin[13]

He wished to learn as much as possible from an experiment so he did not confine himself to observing the single point to which the experiment was directed, and his power of seeing a number of things was wonderful. . . . There was one quality of mind which seemed to be of special and extreme advantage in leading him to make discoveries. It was the power of never letting exceptions pass unnoticed.

Experiments are the work of experimenters. A human subject experiments. In particular, the beginning, the conception of the experiment, is normally the fruit of an intuition, of a presentiment of truth, undemonstrable but sufficiently urgent to motivate an unconditional dedication to many years of work. Relating the genesis of his famous experiment that marked the birth of electromagnetism at the beginning of the eighteenth century, Oersted explicitly indicated some personal references that guided him.

Hans Christian Oersted[14]

As a consequence of the fundamental unity of things, even in his first writings he had postulated that magnetism and electricity were products of the same forces. This opinion, stated incisively, is not new; on the contrary, it was alternatively accepted and rejected for more than two centuries, but until then none of those who accepted the connection was capable of providing a decisive proof. The researchers were expecting to find magnetism in the direction of electric current, in such a way that the north and south poles behaved either like positive and negative electricity, or in precisely the opposite way. All the researches had demonstrated that nothing had been found in this direction.

. . . When preparing the lecture in the course of which he was to deal with the analogy between magnetism and electricity, he thought that if it was possible to produce the magnetic effect by means of electricity, that could not happen in the direction of the current, given that this had been attempted so many times in vain, but had to be the product of a lateral action. . . . Just as a body charged with a strong electric current emits light and heat at every moment, so it could give place in the same way to the magnetic effect that he thought existed.

The observations of the previous century, during which lightning had inverted the poles of a magnetic needle without striking it, confirmed his conviction. The idea came to him for the first time at the beginning of 1820 (on the occasion of a conference on analogy). . . . But this was strictly bound up with his other ideas.

"When I began to examine the nature of electricity the idea came to me that the propagation of electricity consisted in a continuous break in and reconstitution of equilibrium and that it thus comprised an abundance of activities which could not be imagined if they were considered as a uniform current. So I regarded the transmission of electricity as an electrical conflict, and in a particular way my researches on the heat produced by an electric charge obliged me to demonstrate how the two opposed electrical charges which penetrate a heated body with their effect are so confused as to escape all observation, without however having arrived at a perfect stasis, in such a way that they can still demonstrate great activity, albeit under a *form of action* quite different from that which can properly be called electrical. Despite my efforts to justify my idea, this complete disappearance of electrical forces registered by the electrometer, accompanied by a quite considerable activity under another aspect, appeared very improbable to the majority of physicists. Perhaps it is necessary to attribute this reaction in part to the obscurity of the subject, in part to the imperfect way in which I expounded my theory; here it is necessary to confess that new ideas rarely present themselves in all their clarity, even to their author. However, an intimate sense of accord between my theory and the facts inspired in me such a strong conviction of its truth that I dared to base my theory of heat and light on it and thus to attribute to those forces, apparently alternate, a radiating action capable of reaching the greatest distances."

Experiment and Attention: Distrusting the Almost-the-Same

Often the most exhilarating and creative phases of an experiment are the beginning and the end: in the moments of its first conception, when it occurs to someone, the objective aimed at is being discussed, and there is thought about the basic characteristics of the instruments and strategy for measurement and observation; and then at the end, when one is approaching the final result—if one has the good fortune to reach such a goal. But all the space in the middle is a laborious course in territory that is often arid and scattered with hidden pitfalls.

An experiment almost never succeeds the first time, and there has never been an instrument that, after being designed and built, functions correctly the first time that it is turned on. There is always a slow and patient walk to reach the conditions in which the experiment can actually be carried out. The adjustment of the innumerable details of the hardware, the testing and calibration of the instruments, require a great deal of attention, patience, precision, a capacity for endurance. Thus it happens that, to use the words of the bacteriologist Theobald Smith, "It is the care we bestow on apparently trifling, unattractive and apparently troublesome minutiae which determines the result."[15] Perhaps these are the moments when researchers at work exercise fully the clarity of their motivation, their determination in reaching their goal, and hence awareness of the value of it.

A dramatic perception of the long labor of preparing an instrument lies in the moment of launching a space mission, when in an instant many hard years of work are put at risk. Here is the chronicle of the launching of the NASA satellite COBE on November 18, 1989, for the observation of cosmic microwave background radiation.

George Smoot[16]

Saturday morning. I rose early, showered, and dressed warmly. In the predawn darkness, not far away, fifteen years of work were sitting atop many tons of high explosives. If it blew to bits, what would I do? I had been chasing cosmic wrinkles most of my career in cosmology. Would the chase end here, on the Pacific shore, under a fireball that rained metallic debris?

In the twilight, hundreds of us gather outside the Delta site. Numerous buses were waiting. A thousand guests—one of the rocket base's largest turnouts ever—had gathered to see that rare spectacle: a dawn launch. While we watched, the countdown would be handled from the blockhouse, a protected structure about four miles from the launchpad.

I was standing close to Mike Hauser, a fellow principal investigator, and we exchanged silent glances, knowing that of the thousand people in the crowd, the two of us and John Mather had the most invested in the day. On an earlier trip I had seen the rocket up close, and had been aghast at how decrepit it looked, rusting here and there, patched here and there, spot repairs made with Glyptal. Our professional life's work was on top of that thing. We didn't say a word, only silent prayers.

The sky looked calm, clear, inviting. A ribbon of orange glowed in the east. Sunrise was moments away. My watch indicated 6:34 a.m. The launch window was the next twenty minutes, if the satellite was to enter the correct polar orbit, one parallel to the terminator, the shadow line between the day and night halves of Earth. The countdown came down to the last ten seconds.

"Ten, nine, eight, seven, six . . ."

Brows furrowed, muscles tensed; everyone held his breath. At such moments one fears the worst; would the rocket explode in a blinding flash?

". . . five, four, three, two, one . . ."

Someone joked, "If the rocket blows up, everyone hold George down or he'll kill himself!" I shot back: "Kill myself?"

" . . . ignition."

The terrain lit up as bright as the Sun. We could see the rocket lift off, in eerie silence, the launchpad engulfed in flames. Suddenly, seconds later, the sound hit with a roar, vibrating my chest. The air shook. The crowd gasped as the rocket continued its climb, spewing flame and smoke, growling all the way. . . . A half minute into launch, the Delta was traveling at the speed of sound—and still accelerating. We started breathing again. . . .

One of the first great experimenters of the sixteenth century, Nicolas Steno, showed a clear awareness of the intrinsic difficulties of the experimental method, which calls for attention, precision, and patience; it also calls for an unpredictable amount of time. On the other hand, it is difficult to combine haste in reaching the result with certainty of method: this problem is all the more acute when it comes to the mechanisms underlying contemporary scientific research.

Nicolas Steno[17]

Most Serene Grand Duke:

Travellers into unknown realms frequently find, as they hasten on over rough mountain paths toward a summit city, that it seems very near to them when first they descry it, whereas manifold turnings may wear even their hope to weariness. For they behold only the nearest peaks, while the things which are hidden from them by the interposition of those same peaks, whether heights of hills, or depths of valleys, or levels of plains, far and away surpass their guesses; since by flattering themselves they measure the intervening distances by their desire.

So, and not otherwise, is it with those who proceed to true knowledge by way of experiments; for as soon as certain tokens of the unknown truth have become clear to them, they are of a mind that the entire matter shall be straightway disclosed. And they will never be able to form in advance a due estimate of the time which is necessary for loosing that knotted chain of difficulties which, by coming forth one by one, and from concealment, as it were, delay, by the constant interposition of obstacles, them that are hastening toward the end. The beginning of the task merely reveals certain common, and commonly known, difficulties, whereas the matters which are comprised in these difficulties—now untruths which must be overthrown, now truths which must be established; sometimes dark places which must be illumined, and again, unknown facts which must be revealed—shall rarely be disclosed by any one before the clew of his search shall lead him thither. Democritus, not unwisely, was wont to use the illustration of a well, wherein one could scarcely estimate aright the task and time of draining it dry, except by draining it dry, since both the number and the volume of the hidden springs leave the amount of the intake a matter of doubt.

Do not be surprised, therefore, Most Serene Prince, if, for a whole year's time, and, what is more, almost daily, I have said that the investigation for which the teeth of the shark [*Canis Carcharia*] had furnished an opportunity, was very near an end. For having once or twice seen regions where shells and other similar deposits of the sea are dug up, when I observed that those lands were sediments of the turbid sea and that an estimate could be formed of how often the sea had been turbid in each place, I not only over-hastily fancied, but also dauntlessly informed others, that a complete investigation on the spot was the work of a very short time. But thereafter, while I was examining more carefully the details of both places and bodies, these day by day presented points of doubt to me as they followed one another in indissoluble connection, so that I saw myself again and again brought back to the starting-place, as it were, when I thought I was nearest the goal. I might compare those doubts to the heads of the Lernean Hydra, since when one of them had been got rid of, numberless others were born; at any rate, I saw that I was wandering about in a sort of labyrinth, where the nearer one approaches the exit, the wider circuits does one tread.

But I shall not tarry to excuse this tardiness of mine, since it is abundantly evident to you, from long experience, how perplexing is a matter which is involved in a series of experiments.

There is need for great attention so as not to hasten a conclusion, avoiding introducing a preconceived interpretation. It was the intuition of Enrico Fermi, the leader of a celebrated group of Italian physicists, that a firm hand had to be kept on the wheel by sticking to observed facts.

Edoardo Amaldi[18]

After the summer vacation of 1935, Fermi and I found ourselves alone in Rome. . . . Upon resuming work, Fermi and I turned our attention to some results of Bjerge and Westcott, and of Moon and Tilman, who had observed that the absorption of slow neutrons by various elements differed slightly depending on the element used as detector. This fact was not explained by the current theory of the absorption[19] of neutrons by nuclei. This theory predicted a capture cross section inversely proportional to the velocity of the neutrons for all nuclei. This energy dependence was supposed to be valid for such large energy intervals as to certainly cover the energy range of slow neutrons.

We went to work with even greater energy than in the past, as if by our own more intensive efforts we wanted to compensate for the loss of manpower in our group.

We had prepared a systematic plan of attack which we jokingly summarized by saying that we would measure the absorption coefficient of all 92 elements in all possible ways with the 92 elements used as detectors. In jest we added that after combining all the elements two by two, we would also combine them three by three. By this we meant that we would also study the absorption properties of the neutron radiation filtered in several ways.

Actually, after having measured the absorption coefficient of eleven different elements in all possible combinations with seven detectors, we were convinced that the observations of the two English research groups were correct, and in general that the rule that the absorption coefficient of a certain element was greater when the element itself was used as detector was valid. We began to study the particular cases of silver, rhodium and cadmium in great detail. . . .

. . . I, as many others, tended to make a simple picture of the phenomenon; I tried to interpret the different groups of neutrons as different bands of energy. Fermi, however, did not want to accept this description. He, too, was convinced that this was obviously the simplest hypothesis, but maintained that it was not strictly necessary, at least for the moment, and was therefore harmful if introduced into our mental picture. He insisted that one must proceed by reasoning with the observed experimental facts only. The correct interpretation of the nature of the neutron groups would finally emerge as a necessary consequence of the data. He was afraid that a preconceived interpretation, however plausible it sounded, would sidetrack us from an objective appraisal of the phenomenon that confronted us.

Among the characteristics that the experimental method shares with all other methods of knowledge is the possibility of error. In Beveridge's words, "Experimentation, like other measures employed in research, is not infallible."[20] For sure, the human being who tries to apply the method is fallible, and without him the method itself would not exist.

The types of error in the use of the experimental method are very varied and extend from simple distraction to the incorrect interpretation of an emerging clue in such a way as to ignore—more or less consciously—one of the elements in play. *A priori*, in fact there are no factors that can be ignored: only having adequately considered every factor that occurs in the experiment is it possible—and necessary—to leave aside some aspects that prove irrelevant. Small disturbances in a detector or small differences of concentration in a solution can lead to radically different consequences. Therefore, as the following episode related by Primo Levi illustrates, "one must distrust the almost-the-same."

Primo Levi[21]

Distilling is beautiful. First of all because it is a slow, philosophic, and silent occupation, which keeps you busy but gives you time to think of other things, somewhat like riding a bike. Then, because it involves a metamorphosis from liquid to vapour (invisible), and from this once again to liquid; but in this double journey, up and down, purity is attained, an ambiguous and fascinating condition, which starts with chemistry and goes very far. And finally, when you set about distilling, you acquire the consciousness of repeating a ritual consecrated by the centuries, almost a religious act, in which from imperfect material you obtain the essence, the usia, the spirit, and in the first place alcohol, which gladdens the spirit and warms the heart. I took two good days to obtain a fraction of satisfying purity; for this operation, since I had to work with an open flame, I had voluntarily exiled myself to a small room on the second floor, deserted and empty and far from any human presence.

Now I had to distil a second time in the presence of sodium. Sodium is a degenerated metal: it is indeed a metal only in the chemical significance of the word, certainly not in that of everyday language. It is neither rigid nor elastic; rather it is soft like wax; it is not shiny or, better, it is shiny only if preserved with maniacal care, since otherwise it reacts in a few instants with air, covering itself with an ugly rough rind; with even greater rapidity it reacts with water, in which it floats (a metal that floats!), dancing frenetically and developing hydrogen. I ransacked the entrails of the Institute in vain: like Ariosto's Astolfo on the Moon I found dozens of labelled ampoules, hundreds of abstruse compounds, other vague anonymous sediments apparently untouched for generations, but not a sign of sodium. Instead I found a small phial of potassium: potassium is sodium's twin, so I grabbed it and returned to my hermitage.

I put in the flask of benzene the lump of potassium, "as large as half a pea"—so said the manual—and diligently distilled the contents: towards the end of the operation I dutifully doused the flame, took apart the apparatus, let the small amount of liquid in the flask cool off a bit, and then with a long pointed stick skewered the "half pea" of potassium and lifted it out.

Potassium, as I said, is sodium's twin, but it reacts with air and water with even greater energy: it is known to everyone (and was known also to me) that in contact with water it not only develops hydrogen but also ignites. So I handled my "half pea" like a holy relic: I placed it on a piece of dry filter paper, wrapped it up in it, went down into the Institute's courtyard, dug out a tiny grave, and buried the little bedevilled corpse. I carefully tamped down the earth above it and went back up to my work.

I took the now empty flask, put it under a faucet, and turned on the water. I heard a rapid thump; and from the neck of the flask came a flash of flame directed at the window that was next to the washbasin and the curtains around it caught fire. While I was stumbling around looking for some even primitive means to extinguish it, the panels of the shutter began to blister and the room was now full of smoke. I managed to push over a chair and tear down the curtains; I threw them on the floor and stomped furiously on them, while the smoke half blinded me and my blood was throbbing violently in my temples.

When it was all over, when the incandescent tatters were extinguished, I remained standing there for a few minutes, weak and stunned, my knees turned to water, contemplating the vestiges of the disaster without seeing them. As soon as I got my breath back, I went to the floor below and told the assistant what had happened. If it is true that there is no greater sorrow than to remember a happy time in a time of misery, it is true that calling up a moment of anguish in a tranquil mood, seated quietly at one's desk, is a source of profound satisfaction.

The assistant listened to my account with polite attention but with a questioning look: who had compelled me to embark on that voyage, and to distil benzene by going to so much trouble? In a way, it served me right: these are the things that happen to the profane, to those who dawdle and play before the portals of the temple instead of going inside. But he didn't say a word; he resorted for the occasion (unwillingly, as always) to the hierarchical distance and pointed out to me that an empty flask does not catch fire: so it must not have been empty. It must have contained, if nothing else, the vapour of the benzene, besides of course the air that came in through its neck. But one has never seen the vapour of benzene, when cold, catch fire by itself: only the potassium could have set fire to the mixture, and I had taken out the potassium. All of it?

All, I answered; but then I was visited by a doubt, returned to the scene of the accident, and found fragments of the flask still on the floor: on one of them, by looking closely, one could see, barely visible, a tiny white fleck. I tested it with phenolphthalein: it was basic, it was potassium hydroxide. The guilty party had been found: adhering to the glass of the flask there must have remained a minuscule particle of potassium, all that was needed to react with the water I had poured in and set fire to the benzene vapours.

The assistant looked at me with an amused, vaguely ironic expression: better not to do than to do, better to mediate than to act, better his astrophysics, the threshold of the Unknowable, than my chemistry, a mess compounded of stenches, expositions and small futile mysteries. I thought of another moral, more down to earth and concrete, and I believe that every militant chemist can confirm it: that one must distrust the almost-the-same (sodium is almost the same as potassium, but with sodium nothing would have happened), the practically identical, the approximate, the or-even, all surrogates, and all patchwork. The differences can be small, but they can lead to radically different consequences, like a railroad's switch points; the chemist's trade consists in good part in being aware of these differences, knowing them close up, and foreseeing their effects. And not only the chemist's trade.

Experiment and Discovery: Coincidences Happen to Those Who Are Prepared to Recognize Them

To find an adequate method for developing an experiment, there is a need for patience, for attention to all the details, for originality and creativity, for collaboration. Sometimes chance also helps, bringing to light coincidences and individual aspects that were at first ignored; but these are almost always coincidences that are grasped by those prepared to recognize them.

Renato Dulbecco[22]

The first problem was to induce the embryonic cells of the mice to grow like bacteria. This task was greatly facilitated by a specialist in cultures whom I had met on my travels. Stimulated by my visit, he devised a method suitable to the purpose and indicated it to me, sending me all the technical details. It was rather complex, but I succeeded in employing it in my laboratory with the cells I intended to use. To develop the plates I covered the cloth with a thin layer of nutritive agar which would prevent the virus produced by a cell from spreading throughout the culture.

When everything was ready, I began the crucial experiment, infecting the cultures with a very diluted virus. When I had put the plates in the incubator, a restless wait began for me, not least because I did not know how long it would be. That night I slept badly. I got up quickly, ran to the laboratory, but saw nothing interesting; nor did I that afternoon. Another sleepless night and in the morning again nothing new. I began to worry: had I made a mistake? While I was maneuvering myself close to a lamp for better light, I suddenly noticed that in the cellular layer there were about fifty round spots which appeared white with the light behind them but could not be seen against the light. Trying to convince myself in various ways that this was not a dream, but that these were the patches I wanted, I ran to Max's study and said, "Come quickly, I need you."

Max immediately understood that this was something important.

On the way he asked, "Is it working?"

I looked at him with a conspiratorial eye and did not reply. In the basement I took a plate from the incubator, put it in the right light, and asked, "Can you see it?" Max looked, gave me a big smile, and asked, "What day is it?" I have forgotten the precise day, but it was in 1951. A new science was born.

In a short time I made the essential experiments for demonstrating that the method was suitable for testing the virus. I also demonstrated that a patch is produced from a single particle of the virus in such a way that it can be used to purify it. Max encouraged me to present the results to the U.S. National Academy of Sciences in Washington, and I gladly accepted.

. . . On my return to Pasadena I rapidly began experiments which applied my method to important problems of virology. After a short time I noticed something strange. The patches did not look as they had done before. I had to use optimum conditions of illumination; even so, they were very small and indistinct. After some time one couldn't see anything. What had happened? I looked at the cultures in the microscope and succeeded in recognizing small unclear little patches. After the marvelous success was this a new failure? With difficulty I tried many ways of improving the situation, but did not succeed in making my beautiful initial patches reappear.

As often happens, chance came to my aid. One day, in the late afternoon, I went out and began to walk up and down on the grass to relieve my tension. By chance my attention was attracted to the state of the grass. The last time I had looked at it, some weeks before, it was all green; now I could see some yellow stains. Some weeds had infiltrated it; at first they had been invisible because they were green like all the rest, but with the summer heat they had died and had become evident by turning yellow. Eureka! I thought. The patches can't be seen now because it isn't easy to distinguish the dead cells from the live ones. That needs a difference in color. I returned to the laboratory and with the help of my assistant identified a coloring which colored only the live cells and put them in contact with the cells in the agar. Success! The next day patches were very visible, real gaps in the reddish layer, just like those in the bacteriophages.

What a relief! My thought went to the motto of the Accademia del Cimento which I had learned at school: "Test and test again." ✺

If it is true that science moves on the solid ground of experimental verification through deliberately conceived and planned experiments, it is also the case that from time to time such a course is unexpectedly accelerated or modified or changed by an experiment that was not planned, or that was planned to verify something quite different.

Karl Jansky, for example, was godfather to radio astronomy. Jansky was an engineer at Bell Telephone Laboratories who in 1931, while studying the instrumental noise from antennae for radio communication, by chance picked up a distinct signal coming from the sky, more precisely from a region of the sky that corresponded to the center of the Milky Way. Jansky announced his discovery on May 5, 1933, but only after the Second World War did the scientific community seem to take account of the significance of this result: it was the first open breach in the electromagnetic spectrum beyond visible light, and opened the way to dimensions of knowledge greater than those perceived by traditional optical astronomy. Today the figure of Jansky is widely recognized—so much so that the unit of measurement of flux in radio astronomy is named after him—and in 1983, the fiftieth anniversary of the discovery, there was a convention in Virginia in his honor. This is how in that occasion R. Hanbury Brown, a radio astronomer at the University of Sydney, finished his paper.

Karl Jansky[23]

I just want to conclude with a brief word about the moral of the whole of this meeting after listening to the very nice story about Jansky. I have been worrying about what the moral of the story is; if you're an earnest type, like me, you have to draw a moral, especially if you've come half way across the world to listen. It seems to me that the moral of the story that we listened to yesterday about Jansky—the first moral which you would engrave on the side of a building in stone, like you put names like Copernicus and Kepler and Morton Roberts and so on, would be that science cannot dispense with an appeal to experience. That would be the first moral that I would draw from the story of Jansky.

This is a very serious thing I'm talking about, because it's one of the great philosophical illusions of history that everything can be produced from a simple series of laws and that our knowledge of the universe can be reduced to this series of laws. It's one of the great lessons of the science of the last 300 years that you cannot dispense with an appeal to experience. Most of the inventions on which our civilization depends now would not have been supported by a committee of review which gives out money, the sort of committee that I have sat on and probably many of you have as well.

The progress of modern medicine, for example, is almost entirely dependent on the development of X-rays and on the development of antibiotics, both of which were entirely accidental. Both of them were based on experience and neither of them could have been planned. They were not logical. Thus the whole of medical advance is based on accidental experience, not on scientific planning. I will just draw your attention to the fact that if you had a logical committee reviewing inventions, you would have rejected the piano as unworkable, and you would certainly have rejected the bicycle. Anybody given the drawings of a bicycle would reject it at once.

A. Moffet: Not to mention the bumblebee!

Yes, but that's in a different branch of science.

The second thing that I learned from yesterday, and I'm prepared to come 12,000 miles to hear it reinforced, is that science is based fundamentally on freedom of inquiry. This is the deepest lesson, I think, that we can draw from what we've heard of Jansky's work. We usually think, "Well, that's a problem from the past." Freedom of inquiry is all to do with the rejection of authority, Galileo, and the Church, the authority of Aristotle, and so on. We tend to think of freedom of inquiry as a battle which has been won. But of course as one of your Presidents said, I think, "The price of freedom is eternal vigilance." I can't remember which one it was, there must some American here who can tell us! The point is, of course, that freedom of inquiry is something which actually does require vigilance. It is no longer the authority of the Church, or the authority of written documents which restricts the freedom of inquiry in science. In fact, as we saw in the Jansky story, it's not those things that you've got to be careful about and have to watch. The freedom of inquiry can very well be limited by our ideas; the current structure of scientific theory is a framework within which we must work and that restricts us. The construction of very large instruments is another thing which restricts the freedom of people; it gives them an opportunity to make new observations but it restricts their freedom of inquiry. You find yourself working for the instrument, rather than the instrument working for you. ✺

Discovery 4

Any outcome of an investigation is a grace, any step that science takes, it can be made thanks to something that does not depend on science itself. Indeed when one makes a discovery one feels gratitude, experiences a surprise, because nothing is inert, all is alive, all is an act of thanksgiving. LUIGI GIUSSANI

Those who have an excessive faith in their ideas are not cut out for making discoveries. CLAUDE BERNARD

In some strange way, any new fact or insight that I may have found has not seemed to me as a discovery of mine, but rather as something that had always been there and that I had chanced to pick up. SUBRAHMANYAN CHANDRASEKHAR

THE ADVANCEMENT OF scientific knowledge coincides with the series of occasions, minor or major, on which a certain aspect of reality in some way finds the right course and breaks into the horizon of experience. Sometimes the discovery happens as the desired outcome of a long and laborious quest aimed at verifying a well-defined hypothesis; in the preceding chapters we have seen how observation and experiment are decisive elements in the kind of dialogue that is established with nature. At other times the discovery of a new phenomenon happens like an unexpected piece of good news, evidence suddenly introduced by chance and unpredictable factors. But in both cases discovery is "something that happens," something that introduces a discontinuity, something new that cannot be reduced to what was previously known.

In both cases the presence of a positive hypothesis, a hypothesis that guides the moves and strategies of the researchers and polarizes their attention, facilitates enormously their capacity to see and discover what is there. From Christopher Columbus onward there are innumerable episodes that show how seeking to reach a certain territory ends up by reaching a different one, but one that is not necessarily less important than the one initially aimed at.

In the middle of the 1960s, Tony Hewish and the radio astronomy group in Cambridge planned and built a complicated instrument, somewhat rudimentary in appearance, with the aim of identifying weak radio sources, in particular quasars. They covered a vast area with tens of miles of cables and reflective metal rods, all supported by hundreds of wooden posts planted in the ground. This impressive collection of ironware functioned as an optimum receiver of radio waves at a frequency of 81.5 MHz (with a wavelength of more than three and a half meters). Over some months the instrument produced a great mass of data, which Jocelyn Bell Brunell, a young student of Hewish, had the task of analyzing—looking for evidence of interplanetary scintillations. This is how Jocelyn remembers those events of thirty years ago: "We analyzed (in fact not 'we analyzed' but 'I analyzed'!) that interminable roll of data by hand. With four beams each registered with three traces, at a velocity of about twelve inches per hour, we produced more than ninety feet of registered signal per day, seven days a week, and I worked on this for six months, which means that I was personally responsible for analyzing different kilometers of registered signal. The decision to analyze all this by hand was deliberate, partly because of a desire not to connect a new instrument directly to a computer: this was a desire to be able to keep an eye on the data to see what was happening and be sure that all was going well. The other reason for doing the work by hand was that we were not in fact sure that we could succeed in programming a computer in a way which would distinguish between real scintillations and artificial interference."[1] Scrutinizing the traces of the signal one by one, Jocelyn was attracted by a short abnormal oscillation, little longer than a centimeter, that had characteristics that only her skilled eye could distinguish from other known signals or common interference. Analyzed in detail, this trace showed a weak signal with an incredibly rapid and regular periodicity. It was thus that, going in search of the quasar, the young Jocelyn bumped into a new important class of objects, the pulsar, extraordinary creatures that put both physics and our imagination to a hard test.

It is clear that in the case of the pulsars the discovery was the unexpected fruit of research that had been directed at a different object, and we shall see from numerous other examples how this situation is anything but unique. At other times the discovery is even the fruit of pure chance, even the benign consequence of an accidental error. There is a space that cannot be controlled—so to speak—a game that insinuates itself into research, which sometimes allows the scientist unexpectedly to find himself face-to-face with a different prey from the one whose traces he has been seeking to follow.

The awareness that the development and outcome of the investigation are not completely in our hands is very clear to anyone who has had direct experience of research; it has been explicitly expressed by many great scientists. In 1831, in a letter to a friend, Michael Faraday wrote, "I am busy just now again on electromagnetism, and think I have got hold of a good thing, but can't say. It may be a weed instead of a fish that, after all my labor, I may at last pull up."

But even when it answers our precise question, even when the prey captured is the one that we were pursuing, the event of discovery brings novelty and surprise with it. Every discovery is a nonmechanical event, which cannot be reduced to the sum of the moves made or the precautions taken. Only in the light of the response does the mass of hypotheses, attempts, questions raised fully sort itself out, and one can recognize a meaning for every turn in the course. Only the viewpoint offered by the peak allows one to see the complete journey and to understand to the full the value of the whole path.

Many factors contribute to a scientific advance. The brilliance and tenacity of the researchers come first; advances in technology often offer an important if not a decisive factor in discovering a new phenomenon, raising the sensitivity of instruments to unexplored levels; moreover, the ability to manage and coordinate numerous and complex research groups are increasingly decisive for the success of the great experiments of our days, such as of those on elementary particles or space missions. Indeed in no case is scientific discovery a mere consequence of the work done. It is rather the spectacle of a new scenario visible from an observation point that we reached through favorable circumstances and our abilities; a scenario we have the privilege of admiring and communicating.

Discovery and Event: Unique Minutes of a Unique Life

Every discovery has the characteristics of an event rather than of a pure consequence of our methodologies. It is the outcome of a course on which, in addition to our labor and determination, the pattern is made by dramatic turns of events and unforeseen developments. Of course, history tends to forget the failures and hands down only the successful cases; but that does not do away with the fact that the mode of advancement in science is much more spectacular, unforeseeable, and dramatic than is normally thought.

Röntgen, at the end of the nineteenth century, remained literally dumbfounded on seeing for the first time the effects of the X-rays that projected the image of the bones of his hand on a screen. But he was also able to grasp the importance of the incredible phenomenon that he had witnessed, to study it, to repeat the observations, and to document them accurately.

Wilhelm Conrad Röntgen[2]

Wilhelm Conrad Röntgen . . . was born in Lennep, a town in the Rhineland. His mother was Dutch, and his family moved to Apeldoorn in Holland when he was three years old. After studying in Holland, Röntgen went in 1865 to Zurich, where he enrolled in mechanical engineering at the Polytechnic Institute. He studied first with Rudolf Clausius, the great thermodynamicist, and then with August Kundt, to whom he became very close. Kundt's most important contributions were in acoustics, but he is also known for an ingenious, albeit crude, determination of Avogadro's number.

. . . After receiving a doctorate and pursuing further studies, Röntgen became a Privat Dozent, and in 1875, having been appointed a professor of physics at a small German university, he started upon a normal academic career as a good, but not extraordinary, physicist. In 1888 he did an important piece of work showing that the convection current was the same as the conduction current. Such a finding may seem trivial today, but we must remember that Faraday worked hard to convince himself that the electricity from a cell was the same as the electricity produced by an electrostatic machine. . . . Röntgen . . . also made good measurements of specific heats, a standard field of interest in his day. He moved on from one university to another, and in the fall of 1888 assumed his fourth post, a chair at the . . . University of Würzburg, . . . a good university, though not one at the very top. By the beginning of November 1895 Röntgen had written forty-eight papers now practically forgotten. With his forty-ninth he struck gold.

On the evening of November 8, 1895, Röntgen was operating a Hittorf tube and had covered it entirely with black cardboard. The room was completely darkened. At some distance from the tube there was a sheet of paper, used as a screen, treated with barium platinum-cyanide. To his surprise, Röntgen saw it fluoresce, emitting light. Something must have hit the screen if it reacted by emitting light. Röntgen's tube, however, was enclosed in black cardboard, and no light or cathode rays could come out of it. Surprised and puzzled by the unexpected phenomenon, he decided to investigate it further. He turned the screen so that the side without barium platinum-cyanide faced the tube; still the screen fluoresced. He moved the screen further away from the tube, and the fluorescence persisted. Then he placed several objects between the tube and the screen, and all appeared to be transparent. When he slipped his hand in front of the tube, he saw his bones on the screen. . . . He had found "a new kind of rays," as he termed them in his first publication on the subject.

Röntgen was working all alone in his laboratory. He went on working by himself in the days that followed, not mentioning his observations to anyone. . . . Later, he explained his reticence: He had been so astonished at his discovery, so incredulous, that he had felt the need to convince himself over and over again of the existence of these new rays. Finally he fixed his findings on photographic plates and at last became certain of his discovery.

On December 28, 1895, he handed a preliminary paper to the secretary of the Physical-Medical Society in Würzburg. ✺

It was under the impact of Röntgen's discovery of X-rays that Henri Becquerel discovered that uranium salts spontaneously emitted rays of an unknown nature, in some respects similar to Röntgen's X-rays. A compound of uranium put on a photographic sheet surrounded by black card made an impression on a sheet: moreover, these mysterious "uranium rays," like X-rays, released an electromagnetic field, making the surrounding air conductive. So Becquerel had discovered a new phenomenon, but the origin of these rays remained an enigma. It was for Marie Curie to analyze the nature of this phenomenon in depth; she later gave it the name "radioactivity."

The story of the circumstances that led Madame Curie to the discovery of radioactivity—related by her daughter, who gathered together the direct testimony to these events—brings to life the dramatic and enthralling character that research can assume. The gradual awareness of the phenomenon by the young Marie seems almost to be a dance, or perhaps a struggle, with the unknown.

Marie Curie[3]

Becquerel's discovery fascinated the Curies. They asked themselves whence came the energy—tiny, to be sure—which uranium compounds constantly disengaged in the form of radiation. And what was the nature of this radiation? Here was an engrossing subject of research, a doctor's thesis! The subject tempted Marie most because it was a virgin field: Becquerel's work was very recent and so far as she knew nobody in the laboratories of Europe had yet attempted to make a fundamental study of uranium rays. As a point of departure, and as the only bibliography, there existed some communications presented by Henri Becquerel at the Academy of Science during the year 1896. It was a leap into great adventure, into an unknown realm.

The candidate for the doctor's degree set her first task to be the measurement of the "power of ionization" of uranium rays—that is to say, their power to render the air a conductor of electricity and so to discharge an electroscope. The excellent method she used, which was to be the key to the success of her experiments, had been invented for the study of other phenomena by two physicists well known to her: Pierre and Jacques Curie. Her technical installation consisted of an "ionization chamber," a Curie electrometer and a piezoelectric quartz.

At the end of several weeks the first result appeared: Marie acquired the certainty that the intensity of this surprising radiation was proportional to the quantity of uranium contained in the samples under examination, and that this radiation, which could be measured with precision, was not affected either by the chemical state of combination of the uranium or by external factors such as lighting or temperature.

These observations were perhaps not very sensational to the uninitiated, but they were of passionate interest to the scientist. It often happens in physics that an inexplicable phenomenon can be subjected, after some investigation, to laws already known, and by this very fact loses its interest for the research worker. Thus, in a badly constructed detective story, if we are told in the third chapter that the woman of sinister appearance who might have committed the crime is in reality only an honest little housewife who leads a life without secrets, we feel discouraged and cease to read.

Nothing of the kind happened here. The more Marie penetrated into intimacy with uranium rays, the more they seemed without precedent, essentially unknown. They were like nothing else. Nothing affected them. In spite of their very feeble power, they had an extraordinary individuality.

Turning this mystery over and over in her head, and pointing toward the truth, Marie felt and could soon affirm that the incomprehensible radiation was an atomic property. She questioned: Even though the phenomenon had only been observed with uranium, nothing proved that uranium was the only chemical element capable of emitting such radiation. Why should not other bodies possess the same power? Perhaps it was only by chance that this radiation had been observed in uranium first, and had remained attached to uranium in the minds of physicists. Now it must be sought for elsewhere. . . .

No sooner said than done. Abandoning the study of uranium, Marie undertook to examine all known chemical bodies, either in the pure state or in compounds. And the result was not long in appearing: compounds of another element, thorium, also emitted spontaneous rays like those of uranium and of similar intensity. The physicist had been right: the surprising phenomenon was by no means the property of uranium alone and it became necessary to give it a distinct name. Mme Curie suggested the name of *radioactivity*. Chemical substances like uranium and thorium, endowed with this particular "radiance," were called radio elements.

Radioactivity so fascinated the young scientist that she never tired of examining the most diverse forms of matter, always by the same method. Curiosity, a marvelous feminine curiosity, the first virtue of a scientist, was developed in Marie to the highest degree. Instead of limiting her observation to simple compounds, salts and oxides, she had the desire to assemble samples of minerals from the collection at the School of Physics, and of making them undergo almost at hazard, for her own amusement, a kind of customs inspection which is an electrometer test. Pierre approved, and chose with her the veined fragments, hard or crumbly, oddly shaped, which she wanted to examine.

Marie's idea was simple—simple as the stroke of genius. At the crossroads where Marie now stood, hundreds of research workers might have remained, nonplussed, for months or even years. After examining all known chemical substances, and discovering—as Marie had done—the radiation of thorium, they would have continued to ask themselves in vain whence came this mysterious radioactivity. Marie, too, questioned and wondered. But her surprise was translated into fruitful acts. She had used up all evident possibilities. Now she turned toward the unplumbed and the unknown.

She knew in advance what she would learn from an examination of the minerals, or rather she thought she knew. The specimens which contained neither uranium nor thorium would be revealed as totally "inactive." The others, containing uranium or thorium, would be radioactive.

Experiment confirmed this prevision. Rejecting the inactive minerals, Marie applied herself to the others and measured their radioactivity. Then came a dramatic revelation: the radioactivity was a great deal stronger than could have been normally foreseen by the quantity of uranium or thorium contained in the products examined!

"It must be an error in experiment," the young woman thought; for doubt is the scientist's first response to an unexpected phenomenon.

She started her measurements over again, unmoved, using the same products. She started over again ten times, twenty times. And she was forced to yield to the evidence: the quantities of uranium and of thorium found in these minerals were by no means sufficient to justify the exceptional intensity of the radiation she observed.

Where did this excessive and abnormal radiation come from? Only one explanation was possible: the minerals must contain, in small quantity, a much more powerfully radioactive substance than uranium and thorium.

But what substance? In her preceding experiments, Marie had already examined all known chemical elements.

The scientist replied to the question with the sure logic and the magnificent audaciousness of a great mind: The minerals certainly contained a radioactive substance, which was at the same time a chemical element unknown until this day: a new element.

A new element! It was a fascinating and alluring hypothesis—but still a hypothesis. For the moment this powerfully radioactive substance existed only in the imagination of Marie and of Pierre. But it did exist there. It existed strongly enough to make the young woman go to see Bronya one day and tell her in a restrained, ardent voice:

"You know, Bronya, the radiation that I couldn't explain comes from a new chemical element. The element is there and I've got to find it. We are sure! The physicists we have spoken to believe we have made an error in experiment and advise us to be careful. But I am convinced that I am not mistaken."

These were unique moments in her unique life. The layman forms a theatrical—and wholly false—idea of the research worker and of his discoveries. "The moment of discovery" does not always exist: the scientist's work is too tenuous, too divided, for the certainty of success to crackle out suddenly in the midst of his laborious toil like a stroke of lightning, dazzling him by its fire. Marie, standing in front of her apparatus, perhaps never experienced the sudden intoxication of triumph. This intoxication was spread over several days of decisive labor, made feverish by a magnificent hope. But it must have been an exultant moment when, convinced by the rigorous reasoning of her brain that she was on the trail of new matter, she confided the secret to her elder sister, her ally always. . . . Without exchanging one affectionate word, the two sisters must have lived again, in a dizzying breath of memory, their years of waiting, their mutual sacrifices, their bleak lives as students, full of hope and faith.

Barely four years before, Marie had written: "Life is not easy for any of us. But what of that? we must have perseverance and above all confidence in ourselves. We must believe that we are gifted for something, and that this thing, at whatever cost, must be attained." That "something" was to throw science upon a path hitherto unsuspected.

In a first communication to the Academy, presented by Prof. Lippmann and published in the Proceedings on April 12, 1898, "Marie Sklodovska Curie" announced the probable presence in pitchblende ores of a new element endowed with powerful radioactivity. This was the first stage of the discovery of radium. ✺

So it is in the great discoveries, but also in the small ones, that there is something unexpected; and we have seen how some achievements were so unexpected as to leave their discoverers astonished. That is the case with the pioneering observations of cosmic rays by Bruno Rossi, whose results left incredulous not only those who made the discovery but the whole scientific community, and it is the case with the discovery of cosmic microwave background radiation, which brought the Nobel Prize to Arno Penzias and Robert Wilson.

Bruno Rossi[4]

In the discussions at the Rome conference, Walter Bothe and I had reported the results of some experiments by several scientists . . . which suggested the production of secondary particles by the interaction of cosmic-ray particles with matter. But the evidence for this effect was not very definite and, for the most part, it was of a rather indirect nature. Therefore, upon my return to Arcetri, I decided to attempt observing this phenomenon directly. For this purpose, I placed three counters in a triangular configuration so that a single particle traveling along a straight line could not traverse them all. . . . With the counters enclosed in a lead box with walls a few centimeters thick I observed a large number of threefold coincidences. Removing the top part of the box caused the number of coincidences to decrease considerably. It was thus clear that most of the coincidences observed with the box closed were due to groups of associated particles (at least two) arising from interactions of cosmic rays in the box top. Qualitatively, this was the effect I had been looking for. But the size of the effect, as evidenced by the large number of coincidences, was astounding. It showed that cosmic rays were capable of producing an enormously more abundant secondary radiation than any other known rays. So incredible were my results that a German magazine (*Naturwissenschaften*, if I remember correctly) refused to publish my paper. This paper was later accepted by *Physikalische Zeitschrift*, after Heisenberg had vouched for my reliability.

I was greatly excited. Here was a new unexpected phenomenon, a surprising new property of the still mysterious cosmic rays. I continued to experiment using a variety of configurations for the counters, placing upon them, at different distances, layers of lead and of other materials, inserting absorbing shields in different positions. The most significant results obtained in this study . . . show the dependence of the coincidence rate between three counters in a triangular array on the thickness (in mass per unit area) of layers of lead and iron placed above them.

If we focus our attention upon the lead curves . . . we see that the rate of coincidences reaches a maximum between 10 and 20 g/cm^2, which shows that the secondary particles produced in lead have a range of this magnitude. Surprising was the observation that, beyond the maximum, the curves dropped much more rapidly than the known absorption curve of penetrating particles. This meant that the secondary interactions were not produced by the penetrating particles (as I had every reason to expect), but by a different much softer component of the cosmic radiation, whose existence was previously unknown. ✺

David T. Wilkinson and P. J. E. Peebles[5]

Perhaps all discoveries in sciences have some elements of a good mystery story. This one does. In 1964 the major cosmic puzzle was whether the universe is evolving (Big Bang) or Steady State; both ideas had merit, neither had proof. However, the Big Bang had left a deliberate clue—a shadowy remnant of its fiery youth. Three groups of physicists are on the case, each starting from a different premise, and unaware of the others. One group[6] (in Russia) is putting together published theoretical and experimental evidence; they are very close, but misinterpret a clue. Another group,[7] ignorant of the past, starts from the beginning and plods systematically toward the solution. The third group[8]—is looking, very carefully, right at the clue, wondering what it is. Thermal radiation from the Big Bang is about to be discovered. Proving again that nothing is new, the radiation had been predicted 15 years earlier,[9] but not searched for. And at least two published observations—one 25 years old[10]—gave strong evidence for the existence of the radiation prior to its discovery. ✺

Discovery and Innovation: Like Wandering in the Mountains

Not every registration of a phenomenon is a discovery, but only where it introduces something new. A discovery is an event that leads to a new development that cannot be reduced to what is previously known and, as the biologist Theobald Smith has observed, "should come as an adventure rather than as the result of a logical process of thought. Sharp, prolonged thinking is necessary that we may keep on the chosen road, but it does not necessarily lead to discovery."[11] Sometimes the novelty of a discovery is so revolutionary as to shake the very foundations for a whole scientific branch, as happened in biology with the introduction of evolutionary theories, or in physics with the confirmation of the structure of quantum mechanics.

Alfred North Whitehead[12]

The history of science resembles less a smooth machine of progress than a rummage drawer of tools broken and discarded. In the late nineteenth century physics was widely thought of as a closing book. Gravitation had been accounted for by Newton, heat by Maxwell and Boltzmann, electromagnetism by Maxwell and Faraday, with such apparent success that students were cautioned to expect to make no breakthroughs in their careers, but to content themselves with the thought that physics henceforth would consist of merely refining existing "laws." Then in 1900 Max Planck of Berlin discovered the quantum principle, and science was transformed. Almost every "law" that had seemed so solid was altered, diminished or discarded. Alfred North Whitehead, born in 1861, said in the 1930s, "Nothing, absolutely nothing was left that had not been challenged, if not shaken; not a single major concept. This I consider to have been one of the supreme facts of my experience." ✺

However, the new discovery normally does not present itself as something extraneous to the course taken at that moment, something that abolishes the past, but rather as something that completes what we already have before our eyes. Thus, the general theory of relativity does not abolish Newtonian theory but seems more capable of completing it and deepening it. And sometimes, even in science, at the moment when a new idea is proposed, there are many who wonder why that idea did not come to their mind before.

John Burdon Sanderson Haldane[13]

In forecasting the future of scientific research we need to remember a universally valid law: the unexpected always happens. Certainly the future will make any detailed forecast seem stupid. . . .

. . . All science begins with the observation of notable events such as thunderstorms or fevers, and soon establishes generic connections between these and other phenomena, such as the hot season or an infection. The next stage is precise observation and measurement, and often it is very difficult to understand that to measure in this way is the best way of explaining the phenomena that one is investigating. In the cases of both thunderstorms and fevers, the indication has come from the measurement of the length of columns of mercury in a barometer; but what prophet could ever have foreseen this? There follows a phase in which innumerable graphics and tables of figures are compiled, the desperation of students and the object of sarcasm from the man in the street, and unexpectedly a new idea arises from this muddle, easy to grasp, the idea of a cyclone or an electron, a bacillus or an antitoxin, and everyone asks why this had not been thought of before. ✺

The innovation sometimes emerges suddenly, at others from patient and tenacious work, from enterprises that are at first sight impossible. The transition to the dawn of a discovery often happens after a long night and a slow dawn. Einstein, speaking of the origin of the theory of relativity, wrote: "The years of searching in the dark for a truth that one feels but cannot express, the intense desire and the alternations of confidence and misgiving until one breaks through to clarity and understanding are known only to him who has himself experienced them."[14]

Helmholtz compared himself with a man wandering in the mountains who after hard climbing and a series of attempts and errors, finally finds the right path. The Nobel Prize–winner Max Perutz relates in an interview his advance toward the discovery of the structure of hemoglobin, which took twenty-two years, and compares the degree of newness thus introduced to the experience of the "discovery of a new continent."

Hermann von Helmholtz[15]

In 1891 I was able to solve a few problems in mathematics and physics including some that the great mathematicians had puzzled over in vain from Euler onwards. . . . But any pride I might have felt in my conclusions was perceptibly lessened by the fact that I knew that the solution of these problems had almost always come to me as the gradual generalization of favourable examples, by a series of fortunate conjectures, after many errors. I am fain to compare myself with a wanderer on the mountains who, not knowing the path, climbs slowly and painfully upwards and often has to retrace his steps because he can go no further—then, whether by taking thought or from luck, discovers a new track that leads him on a little till at length when he reaches the summit he finds to his shame that there is a royal road, by which he might have ascended, had he only had the wits to find the right approach to it. In my works, I naturally said nothing about my mistake to the reader, but only described the made track by which he may now reach the same heights without difficulty. ✺

Max Perutz[16]

Question: You received the Nobel Prize for chemistry for identifying the structure of hemoglobin and you have contributed to important discoveries in molecular biology. How and why did you come to be occupied with protein molecules?

Perutz: The secret of living cells lies in proteins. And the chemistry of life depends on protein molecules which work together in a marvelously ordered way. In the 1930s, when I began, it had just been discovered that all the chemical reactions which take place in the cell are catalyzed by enzymes and that all the enzymes are proteins; but very little was known of the chemical foundation of these compounds: no one had any idea of their structure and how they functioned. Proteins were "black holes."

We recognized that without knowing the structure of the proteins it was impossible to know the mechanism of their action: this seemed at that time to be the central problem of biology. I was optimistic, but my colleagues thought that it was crazy to tackle such an impossible problem and many thought that I was wasting my life on something that I would never be in a position to prove. Sometimes even I despaired and asked myself whether they were not right, but in one way or another I succeeded in making progress.

Question: Confronted with a totally unexplored field of research, what instruments and investigative methods did you use?

Perutz: In 1937 I began to study hemoglobin: it was easy to find the molecule and it seemed to be one of the few proteins which could be crystallized; as Joseph Barcroft once said, all that was known at that time about hemoglobin could be written on the back of an envelope.

There was a method, crystallographic analysis by means of X-rays, which was used by physicists to emphasize the three-dimensional disposition of the atoms in the crystalline structure. It had been developed by William Lawrence Bragg and made it possible to work out the structure of cooking salt: by analyzing the crystals the position of the atoms of chlorine and sodium within them had been identified.

When I began to work at Cambridge no one had yet broken down the structure of a simple composite such as common sugar, but I was ambitious enough to want to break down the extraordinary complex structure of protein molecules. It was known that they contained thousands of atoms and I had no idea how they could be arranged, but I was convinced that this problem could be resolved with this method of analysis.

Question: What difficulties did you have to face?

Perutz: My first results had shown that hemoglobin was a spheroid with a well-defined atomic structure in which four *eme* groups were approximately parallel to one another: this was a new concept, because up to that point the proteins were thought of as colloids without a precise structure. The problem was how to proceed and the way would still have been a long one.

If a crystal is exposed to a source of X-rays, a figure of diffraction can be obtained on a photographic film put underneath it: it consists of a set of points. The intensity of the different points depends on the disposition of the atoms in the crystal. However, the information thus obtained is not sufficient to work out the structure: it identifies the width of the diffracted rays but not their phases. In fact, each of these points is produced by a wave. If it was possible to go behind every individual wave to a precise atom of crystal, one would find either a maximum breadth or a minimum or an intermediate point. Without this information for each one of the thousands of points, the information registered on the photographic film would be useless. This seemed impossible to discover, but it was the enigma that I had to resolve. Fifteen days later I set to work and measured thousands of points.

Question: When did the black hole begin to yield up its secrets?

Perutz: In 1953, sixteen years after I had begun, I discovered the way to understand whether these points were on the crest or in the trough of a wave. I thought of comparing the dispositions of the points obtained from the original protein with that obtained from a protein with which I had "attacked" an atom of heavy metal, mercury. I knew that whether or not they were on the crest of the wave could have produced slight changes in the figure of refraction.

I was in the camera oscura with my heart in my mouth while I was developing these images; I compared the two figures of diffraction, saw the difference, and realized that the problem had been solved. This propelled me up three floors to Professor Bragg and I asked him to come down: at first glance he accepted that the way was open. It was a moving movement and I admired Bragg because he had been thinking about this problem for years and now it had been solved by a younger man than him; he showed no resentment and continued to say that I had discovered a gold mine.

I thought that I would arrive immediately at the structure, but I had not taken account of the technical difficulties.

Another six years of experiments followed. In 1959, one September morning a series of maps emerged from the computer which, for the first time, showed what the structure of the molecule really was. I ran to buy sheets of plastic, drawing pins and a wooden table: on the table I put the sheets on which I had cut out the forms shown by the computer; I put them on top and unexpectedly found myself facing a three-dimensional molecule; it was something that no one had ever seen, and it was fantastic, an experience comparable to the discovery of a new continent.

Discovery and Imagination: Between Day Science and Night Science

"Every discovery consists in seeing what everyone has seen and in thinking what no one has ever thought" (Albert Szent-Györgi).

A discovery is not generally the result of a deductive journey. Human reason in scientific experience is used with a breadth that greatly exceeds that limited—and only this is irreplaceable—capacity that we call "logic" or "deduction." Reason is an eye on reality, an opening that gathers and adapts itself to the real, and that aims to assert what exists as a datum; reason applied to scientific knowledge seeks to describe and synthesize the form of order that connects the phenomena. In this dynamic the subject makes an essential creative contribution without which the synthesis is not achieved. To subject the imagination to the fact, to subject thought to observation, does not in fact diminish imagination and thought but on the contrary gives them their healthy and solid basis, making an authentic creativity possible.

Leo Esaki[17]

Einstein loved to repeat, "If you want to know how scientists proceed, do not listen to what they say but watch what they do." We have to admit that science too has dual characteristics. It has a logical, objective, cold, and rational or rigorous face—the aspect of the finished product that appears in manuals and is presented to the public in conventions and conferences. I am convinced that Einstein meant that this product does not help much in understanding the true nature of science.

The other face is fantastic, subjective, individualistic, intuitive, and lively, and reflects the process by which the new is created. It is a process based on perception and inspiration, obviously supported by an acute mind. Scientists can use their imagination to grope forward, in a desperate struggle of trial and error, seeking out the secrets of the universe. If by chance they find a solution and their efforts are rewarded, then they can truly be happy: that rarely happens. This is the creative process which is the essence of science. This is what Einstein meant when he said, "Look at what they do."

François Jacob, Nobel Prize winner for medicine, used the expression "day science" to describe the logical side and "night science" to describe that of the imagination. They are complementary; both are necessary to the progress. But the germ of discovery or of a new theory is always in the lap of "night science."

Peter B. Medawar[18]

The major defect of the hypothetico-deductive scheme, considered as a formulary of scientific behavior, is its disavowal of any competence to speak about the generative act in scientific enquiry, "having an idea," for this represents the imaginative or logically unscripted episode in scientific thinking, the part that lies outside logic. The objection is all the more grave because an imaginative or inspirational process enters into all scientific reasoning at every level: it is not confined to "great" discoveries, as the more simple-minded inductivists have supposed.

Scientists are usually too proud or too shy to speak about creativity and "creative imagination"; they feel it to be incompatible with their conception of themselves as "men of facts" and rigorous inductive judgments. The role of creativity has always been acknowledged by inventors, because inventors are often simple unpretentious people who do not give themselves airs, whose education has not been dignified by courses on scientific method. Inventors speak unaffectedly about brain waves and inspirations: and what, after all, is a mechanical invention if not a solid hypothesis, the literal embodiment of a belief or opinion of which mechanical working is the test?

Intuition takes many different forms in science and mathematics, though all forms of it have certain properties in common: the suddenness of their origin, the wholeness of the conception they embody, and the absence of conscious premeditation. . . .

The scheme of thought I have outlined . . . explains the balance of faculties that should be cultivated in scientific research. Imaginativeness and a critical temper are both necessary at all times, but neither is sufficient. The most imaginative scientists are by no means the most effective; at their worst, uncensored, they are cranks. Nor are the most critically minded. The man notorious for his dismissive criticisms, strenuous in the pursuit of error, is often unproductive, as if he had scared himself out of his wits—unless indeed his critical cast of mind was the consequence rather than the cause of his infertility.

. . . The scientific method is a potentiation of common sense, exercised with a specially firm determination not to persist in error if any exertion of hand or mind can deliver us from it. Like other exploratory processes, it can be resolved into a dialogue between fact and fancy, the actual and the possible; between what could be true and what is in fact the case. The purpose of scientific enquiry is not to compile an inventory of factual information, nor to build up a totalitarian world picture of natural Laws in which every event that is not compulsory is forbidden. We should think of it rather as a logically articulated structure of justifiable beliefs about nature. It begins as a story about a Possible World—a story which we invent and criticize and modify as we go along, so that it ends by being, as nearly as we can make it, a story about real life.

Among the many possible examples that document the role of the imagination in a scientific discovery, we have chosen the fortunes of Ernest Rutherford, related by Max Perutz, coming to grips with the experiment carried out by Geiger and Marsden. They intended to study alpha particles, which they used as projectiles fired at great speed at a sheet of gold foil, and arrived at a disconcerting result. It was Rutherford's imagination that provided a solution to the enigma, advancing a hypothesis that did not look at the projectiles but at the target. This was the discovery of the structure of the atom.

Ernest Rutherford[19]

Rutherford died before I had any chance of attending his lectures. After his death spare reprints of his scientific papers were laid out in the attic of the lab, and research students were allowed to help themselves. I still have those reprints and look to them as models of the way science should be done. The experimental results are reported lucidly and concisely, with a minimum of jargon and mathematics; every conceivable objection is excluded by experiment rather than by argument, leaving no possible loopholes in the conclusions. From those papers and from the atmosphere around the place I became imbued with Rutherford's values, which Wilson characterizes as loyalty to your laboratory, extreme devotion to hard experimental work, and strong aversion to speculation beyond what is justified by the experimental results. When Crick and Watson lounged around, arguing about problems for which there existed as yet no firm experimental data instead of getting down to the bench and doing experiments, I thought they were wasting their time. However, like Leonardo, they sometimes achieved most when they seemed to be working least, and their apparent idleness led them to solve the greatest of all biological problems, the structure of DNA. There is more than one way of doing good science.

Did Rutherford make his discoveries by the hypothetico-deductive method postulated by modern philosophers of science? Like Napoleon, who did not win his battles by any fixed strategy, Rutherford did not follow any one method. A favorite one, stressed by Wilson, consisted of pursuing any anomalous or unexpected effect, but any intelligent scientist does that. Rutherford's strength lay in always being on the lookout for such effects and being extremely observant in spotting them. The most spectacular of those unexpected effects was obtained in 1909 by two of Rutherford's collaborators, Hans Geiger and Ernest Marsden, when they watched the scattering of alpha particles by a gold foil (alpha particles are helium nuclei shot out by their radium source). Most of the particles passed straight through the gold, but about one in eight thousand was reflected backward: in Rutherford's words, "as though you had fired a 15-inch shell at a piece of tissue paper and it had bounced back at you." This observation provided the first clue to the structure of the atom. It showed that it is a solar system in which nearly all the weight is concentrated in a tiny positively charged sun, the nucleus; this nucleus is surrounded by almost weightless negatively charged planets, the electrons. An alpha particle is itself a tiny atomic nucleus, and a gold foil therefore looks to it like empty space, in which the heavy gold nuclei are distributed so thinly that the chance of hitting one is quite small, but if the much lighter alpha particle does hit one of them, it is bounced back hard by its positive charge.

Geiger and Marsden's experiment had been designed to tell them something about alpha particles rather than about the gold foil, and Rutherford had had no working hypothesis of the atom before their totally unexpected result. I once held this up to Sir Karl Popper as an argument against the hypothetico-deductive method, which postulates that scientists advance by first formulating hypotheses and then designing experiments to test them, rather than the inductive method, which consists of deriving theories from observations. Popper retorted that neither Geiger nor Marsden had been able to derive the structure of the atom from their observations. Therefore, it was not implicit in them but was the brainchild of Rutherford's powerful physical insight. I have now learned that even for Rutherford the truth did not dawn in a flash; it took him eighteen months to work it out, which shows that he needed more than the bare observations. On another occasion in Cambridge many years later, two of Rutherford's collaborators, Mark Oliphant and John Cockcroft, obtained a result that neither they nor Rutherford could at first understand. It kept Rutherford awake. He turned it over and over in his mind, until at 3:00 a.m. he suddenly knew the answer. Excitedly he telephoned Oliphant to wake him up and tell him what it was. Here again Rutherford's imagination solved the riddle: they had discovered a light isotope of helium, helium 3, which has since found an important use in work at temperatures near absolute zero. ✺

Seen from the perspective of "science in action," even the famous "Popperian" idea of falsification as the ultimate criterion for scientific knowledge does not seem sufficient to describe the dynamic of discovery: the scientist "seeks discovery" and wants to see confirmation of what his imagination has hypothesized.

Michael Polanyi[20]

I have spoken of the excitement of problems, of an obsession with hunches and visions that are indispensable spurs and pointers to discovery. But science is supposed to be dispassionate. There is indeed an idealization of this current today, which deems the scientist not only indifferent to the outcome of his surmises, but actually seeking refutation. This is not only contrary to experience, but logically inconceivable. The surmises of a working scientist are born of the imagination seeking discovery. Such effort risks defeat but never seeks it; it is in fact his craving for success that makes the scientist take the risk of failure. There is no other way. Courts of law employ two separate lawyers to argue opposite pleas, because it is only by a passionate commitment to a particular view that the imagination can discover the evidence that supports it. ✺

A scientific theory is also "discovered," not simply invented as a brilliant projection of a scheme on reality. The theory is good when it says something true about the world, even provisionally. John Polkinghorne, having narrated the historical circumstances of the developments in the 1960s–1970s of the theory of the electroweak interaction, concludes by observing that it is not a matter of a tacit accord between the scientist but a discovery of what is really the physical world.

John Polkinghorne[21]

The tale is clearly not one of majestic inevitable intellectual advance. It is an untidy story of human endeavour, incorporating both insight and error. Yet it is a tale of real progress in understanding the physical world. The experiments of the 1970s were more accurate and better analysed than the experiments of the 1960s had been. There were objective grounds for preferring the former's conclusions. The new theory was elegant and well understood. The community of science had gained knowledge: there were neutral currents; electromagnetism and the weak nuclear force were aspects of a single underlying phenomenon. This was not just the result of a tacit agreement among the invisible college of high energy physicists to see things this way. The understanding gained was a discovery of what the physical world is actually like.

Many philosophers of science are unwilling to accept that judgement. . . . Scientific theory is not logically entailed by experiment but rather it is read out of empirical knowledge by a personal act of creativity. That creative insight is sifted and endorsed within the truth-seeking community of scientists. Philosophers find it difficult to recognize how resistant nature is to yielding up its secrets, how very hard it is to discover a theory possessing economy, plausibility, and wide empirical adequacy. They suspect, somehow, that there are many such theories lying around, undisclosed because of the scientists' lazy acceptance of the first socially agreed version that comes their way.

Discovery and Intuition: In Free Fall

It can happen that a sudden intuition, an idea that seems to shine out, suddenly resolves the problem. And just as the discovery of a new phenomenon is not purely the consequence of a procedure, so the formation of an idea does not coincide with a deliberate, voluntary act. "To have an idea" is something that happens rather than something that we do—and this is so true that when it happens we ourselves are the first to be amazed. Intuition is evidently a singular leap, a discontinuity that cannot be rationalized, that cannot be put in a container. It is most similar to the unforeseen inspiration of the artist that in a moment suddenly takes on an unexpected space or form. Perhaps it can be said that the capacity for intuition is related to the habit of seeking links between different phenomena: intuitive brilliance follows the attitude to recognize signs of an analogy between different situations as soon as they are manifested.

Einstein relates the precise moment when he was struck by the unexpected thought that led him to the general theory of relativity.

ALBERT EINSTEIN[22]

I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me: "If a person falls freely he will not feel his own weight." I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation. ✺

And this is how Enrico Fermi relates to Subrahmanyan Chandrasekhar the "unexpected inspiration" that in October 1934 led him to use paraffin, rather than lead, in the memorable experiment of bombarding uranium with neutrons—an intuition that won him the Nobel Prize.

ENRICO FERMI[23]

I will tell you how I came to make the discovery which I suppose is the most important one I have made. . . . We were working very hard on the neutron induced radioactivity and the results we were obtaining made no sense. One day, as I came to the laboratory, it occurred to me that I should examine the effect of placing a piece of lead before the incident neutrons. And instead of my usual custom, I took great pains to have the piece of lead precisely machined. I was clearly dissatisfied with something; I tried every "excuse" to postpone putting the piece of lead in its place. When finally, with some reluctance, I was going to put it in its place, I said to myself, "No! I do not want this piece of lead here; what I want is a piece of paraffin." It was just like that: with no advanced warning, no conscious, prior, reasoning. I immediately took some odd piece of paraffin I could put my hands on and placed it where the piece of lead was to have been. ✺

This was how that the mythical "Via Panisperna boys" finally succeeded in producing and understanding the phenomenon of artificial radioactivity. It is not clear what guided Fermi's mind to use paraffin (a substance rich in hydrogen atoms) instead of lead. The fact is that within the space of a few hours Fermi had the correct explanation: the neutrons are far more effective in producing radioactivity since they have more time to interact with the nuclei, being slowed down by collision with the protons of the paraffin. The very evening of the experiment the historic communication was sent to the review *Ricerca Scientifica* with the title: "The action of hydrogenated substances on radioactivity produced by neutrons."

Also in the mathematical field, intuition often anticipates and illuminates the way of rigorous demonstration. It was Carl Friedrich Gauss who said, referring to a theorem on which he was working, "I have the result, but not yet how I arrived at it." And in this passage from the great mathematician Poincaré it is difficult to believe how the understanding of hard and complex parts of his work repeatedly presented themselves to him in completely unexpected ways and circumstances.

Henri Poincaré[24]

For a fortnight I had been attempting to prove that there could not be any function analogous to what I have since called Fuchsian functions.[25] I was at that time very ignorant. Every day I sat down at my table and spent an hour or two trying a great number of combinations, and I arrived at no result. One night I took some black coffee, contrary to my custom, and was unable to sleep. A host of ideas kept surging; I could almost feel them jostling one another, until two of them coalesced, so to speak, to form a stable combination. When morning came, I had established the existence of one class of Fuchsian functions, those that are derived from the hypergeometric series. I had only to verify the results, which only took a few hours.

Then I wished to represent these functions by the quotient of two series. This idea was perfectly conscious and deliberate; I was guided by the analogy with elliptical functions. I asked myself what must be the properties of these series, if they existed, and I succeeded without difficulty in forming the series that I have called Theta-Fuchsian.

At this moment I left Caen, where I was then living, to take part in a geological conference arranged by the School of Mines. The incidents of the journey made me forget my mathematical work. When we arrived at Coutances, we got into a break to go for a drive, and just as I put my foot on the step, the idea came to me, though nothing in my former thoughts seemed to have prepared me for it, that the transformations I had used to define Fuchsian functions were identical with those of non-Euclidian geometry. I made no verification, and had no time to do so, since I took up the conversation again as soon as I had sat down in the break, but I felt absolute certainty at once. When I got back to Caen I verified the result at my leisure to satisfy my conscience.

I then began to study arithmetical questions without any great apparent result, and without suspecting that they could have the least connexion with my previous researches. Disgusted at my want of success, I went away to spend a few days at the seaside, and thought of entirely different things. One day, as I was walking on the cliff, the idea came to me, again with the same characteristics of conciseness, suddenness, and immediate certainty, that arithmetical transformations of indefinite ternary quadratic forms are identical with those of non-Euclidian geometry.

Returning to Caen, I reflected on this result and deduced its consequences. The example of quadratic forms showed me that there are Fuchsian groups other than those which correspond with the hypergeometric series; I saw that I could apply to them the theory of the Theta-Fuchsian functions other than those which are derived from the hypergeometric series, the only ones I knew up to that time. Naturally, I proposed to form all these functions. I laid siege to them systematically and captured all the outworks one after the other. There was one, however, which still held out, whose fall would carry with it that of the central fortress. But all my efforts were of no avail at first, except to make me better understand the difficulty, which was already something. All this work was perfectly conscious.

Thereupon I left for Mont-Valérien, where I had to serve my time in the army, and so my mind was preoccupied with very different matters. One day, as I was crossing the street, the solution of the difficulty which had brought me to a standstill came to me all at once. I did not try to fathom it immediately, and it was only after my service was finished that I returned to the question. I had all the elements, and had only to assemble and arrange them. Accordingly I composed my definitive treatise at a sitting and without any difficulty.

In this personal and very human passage from Francesco Severi, the dimensions of intuition and imagination are openly emphasized as crucial to the work of the mathematician. And a human presence appears, that of his wife, as indispensable company in the toil of work and in sharing joy at the moment of the successful intuition.

Francesco Severi[26]

I would now like to say a word about the nature of our scientific work, also so that account can be taken of what a mathematician can do when he is seeking innovation in his own science. Many times people have said to me, "But hasn't mathematics been finished for thousands of years? What is the point of going on today?"

It is a grave error to think that mathematics exhausted its own achievements two millennia ago, with Euclid and Archimedes. After these great figures, who laid the foundations, every century and, one could add, every civilized people has left indelible marks on our science, enriching it with thoughts, concepts, theories, new technical instruments for calculation, ratiocination, and presentation, of which those who only know the elements cannot have the slightest idea.

Today the field is so vast that no mathematician at present can say that he can embrace all its knowledge with his own brain, and for that reason theories capable of broad and profound syntheses have been constructed, powerful instruments of calculation and geometric or algebraic representation. The problems are never exhausted: through every new mathematical discovery the horizon which opens up ahead gets wider. Hardly had I become involved in the life of mathematics than I felt myself strongly and tenaciously attracted by the vastness of what was known and by a lively (though not humble) but natural desire to contribute with some new knowledge. I set to work with such ardor that after an exhausting year of concentrating on the objective of my research, assimilating new knowledge and becoming familiar with its use, I was so tired that I felt discouraged, fearing that my strength would be not sufficient for the tasks that I had set myself. In this state of mind, needing a time of rest and encouragement in the loving warmth of my family, the levelheadedness and comfort of my beloved Compagna were also precious and crucial for me; she immediately saw how I had to be treated and often sympathized with me. Thus I succeeded in overcoming the crisis and began to resume my course.

Almost sixty years have passed since then, but the memory of the period is alive in my mind, as is the memory and the impression of enthusiasm and satisfaction that the scientist experiences on his first scientific conquest, however small and modest.

I have always said, and now repeat, that if I had to choose what I would do in a second earthly life I would again occupy myself with science, with scientific research, with teaching and proselytism, the need for which grows, as is natural, as a consequence of attachment to a science and to the scheme of its fundamental insights.

The satisfaction that scientific work has given me certainly depends on the fact that ours is a kind of artistic work, in the sense that scientific production, especially in mathematics, which is an abstract and not an experimental science, is not possible simply by relying on the logical endowments of the brain, but also needs the force of intuition and the fervor of the imagination. It is for this reason that many times the resolution of a question which has occupied someone for a long time unexpectedly comes to mind, with sudden inspiration.

I must recall in this connection an episode from June 1904 in Pisa, before I became professor in Parma. . . . I had been preoccupied for some years with a controversial question, which at that time was the order of the day, for the further development of algebraic geometry to which I had made the majority of my contributions. I had finished a scholarly book and in an afternoon of the suffocating heat of Pisa I was lying on my bed for a while, to find respite from the heat. However, my mind suddenly returned, without any involvement of my will, to the controversial question that I have just mentioned. Suddenly there came to mind a calculation I had made many months previously: at that time I had not attached any importance to it for my purpose. Unexpectedly it occurred to me that this calculation already contained the key to the resolution of the question. In this state of mind I leaped from the bed and with difficulty looked for the relevant scrap of paper, months old. Things were in fact as my intuition had told me. That evening I was able to send an academic note to the Lincei, with the resolution of this long-standing question. My wife was as delighted as I was. ✺

Discovery and Company: Invariably, One of Us Would Come Up with an Idea

Often intuition is facilitated or stimulated by dialogue with a friend, not necessarily someone who is in a position to prompt new ideas but a friendly presence who really listens. In fact, reason is not unconnected with the rest of the human person—even when that person is a researcher! And reason derives energy, creative capacity, and certainty from an emotionally significant relationship, from the company of someone else to whom one is welcome. The fundamental intuition of the theory of specific relativity came to Einstein through a discussion with a friend in Berne, as Einstein himself has testified.

Albert Einstein[27]

As a student I got acquainted with the unaccountable result of the Michelson experiment[28] and then realized intuitively that it might be our incorrect thinking to take account of the motion of the earth relative to the aether, if we recognized the experimental result as a fact. In effect, this is the first route that led me to what is now called the special principles of relativity. . . . I had just a chance to read Lorentz's 1895 monograph, in which he had succeeded in giving a comprehensive solution to problems of electrodynamics within the first approximation, in other words, as far as the quantities of higher order than the square of the velocity of a moving body to that of light were neglected. . . .

I took into consideration Fizeau's experiment, and then attempted to deal with the problems on the assumption that Lorentz's equations concerning the electron should hold as well in the case of our system of coordinates being defined on the moving bodies as defined in vacuo. At any rate, at that time I felt certain of the truth of the Maxwell–Lorentz equations in electrodynamics. All the more, it showed to us the relations of the so-called invariance of the velocity of light that those equations should hold also in the moving frame of reference. This invariance of the velocity of light was, however, in conflict with the rule of addition of velocities we knew of in mechanics.

I had a great difficulty in resolving the question why the two cases were in conflict with each other. I had wasted almost a year in fruitless considerations, with a hope of some modification of Lorentz's idea, and at the same time I could not but realize that it was not an easy puzzle to solve at all.

Unexpectedly a friend of mine in Bern then helped me. That was a very beautiful day when I visited him and began to talk with him as follows:

"I have recently had a question which was difficult for me to understand. So I came here today to bring with me a battle on the question." Trying a lot of discussions with him, I could suddenly comprehend the matter. Next day I visited him again and said to him without greeting: "Thank you. I've completely solved the problem." My solution was really for the very concept of time, that is, that time is not absolutely defined but there is an inseparable connection between time and the signal velocity. With this conception, the foregoing extraordinary difficulty could be thoroughly solved. Five weeks after my recognition of this, the present theory of special relativity was completed.

Discoveries are almost always interwoven with acts of sharing, meetings, sympathy, human occasions. Science is done by human beings, often young, who find themselves sharing years of work crammed with labor, delusions, satisfaction. Often antagonisms are created, as in any field. But among scientists, when they participate in a group, real friendships can come about, or at least periods or moments of intense friendship, supported by the awareness of being engaged in the same struggle with a great mystery that they confront.

In the next two passages. one can read between the lines the tone of confidence, familiarity. and friendship that binds the persons involved.

Sheldon Lee Glashow, John Iliopoulos, Luciano Maiani[29]

Maiani arrived in Cambridge and was delighted to find Glashow and Iliopoulos had similar interests—so similar, in fact, that they immediately informed him that his ideas could not possibly be correct.

"We started discussing furiously," Maiani said. "Because I was defending my work, and they were attacking it, there was always a lot of discussion in which two people were attacking a third one." He laughed. "I was a fool."

"We finally convinced him that what he had done with Cabibbo was not relevant," Iliopoulos recalled. "I don't know how long it took, but he finally admitted it." Nonetheless, Iliopoulos and Glashow liked the essential idea of computing the Cabibbo angle by getting rid of divergences. From his thesis, Glashow also knew that using a Yang–Mills formulation also got rid of infinities; he had even claimed, erroneously, that local gauge symmetry eliminated all of them. "Every day," Iliopoulos said, "invariably, one of us would come up with an idea. Then the other two would prove to him he was wrong. We tried all sorts of different recipes, and nothing worked. There were long calculations and trying to—I mean, there was this angle that we tried to untangle—it was impossible. This took us some time, and we got frustrated. And then we really convinced ourselves—we didn't have any rigorous proof—that there was no solution in the then-standard model of three quarks and four leptons. We couldn't renormalize it. So then we started to change things in other ways. The first thing we tried to do was put in more leptons."

After playing with leptons for a while, they gave up and plugged in a fourth quark, which Glashow, remembering his 1964 paper, again called charm. Almost at once they realized they were onto something. All three men liked the obvious tidiness of four quarks and four leptons. Moreover, adding in an extra quark to the equations made many more divergences vanish; the theory became much neater. . . . Finally, Glashow at last realized that charm canceled the possibility of neutral currents for strange particles, neatly removing one of the major problems of his SU(2) x U(1) model. He told us, "What I don't understand is why I forgot that charm was relevant for so long. But how often can you forget something for six years and have no one take you up on it? The next paper, with Iliopoulos and Maiani, uses that observation to solve a major problem of physics. But nobody else was aware of the problem, let alone finding the solution."

The problem came from Maiani's work with Cabibbo. . . . Glashow, Iliopoulos, and Maiani calculated that experimenters should already have seen such decays, and took their absence as an indication that charm was on the job. They were hugely pleased; physicists routinely predicted new particles, but it was not often that one got a chance to postulate the existence of an entirely new state of matter comprised of whole families of charmed particles.

Excited, the three theorists took their work to the office of MIT theorist Francis Low, and talked it over with anyone who came in. They mentioned that charm might fit into an SU(2) x (U)1 model. One of the physicists who wandered by was Steven Weinberg. Glashow laid out the case for charm, mentioning that it might fit into some kind of Yang–Mills scheme. A spectacular failure in communication ensued. Weinberg did not see the relevance of charm to his work three years before. Indeed, in Maiani's recollection, he reacted with instinctive dislike to the extreme lack of economy implicit in introducing whole families of unknown particles to shrink the reaction rate of an obscure class of particle decays. His momentary lapse—together with those of Glashow and Iliopoulos, who knew of Weinberg's paper—meant that the three men continued to put the masses in by hand, instead of employing symmetry breaking. . . .

All three were convinced of the existence of charm, but Glashow's certainty was the most ebullient. Glashow, Maiani, and Maiani's wife went to a Cambridge hangout with the curious name of Legal Sea Food. Over the meal, Glashow informed Maiani's wife that he was extremely pleased with what has come to be known as the GIM mechanism for avoiding strangeness-changing neutral currents. She asked if it was important. Glashow replied, "It will be in the textbooks." ✺

A glimpse of the atmosphere within the famed society of Via Panisperna is here described by Emilio Segrè.

Enrico Fermi (and His Group)[30]

I [Emilio Segrè] vividly remember one of my first visits to the laboratory: Fermi and Rasetti—one short and stocky, the other tall and lean, both in not-too-clean, gray smocks—focusing the fringes of a Jamin interferometer on the slit of Hilger quartz spectrograph encased in shiny mahogany. They tried to awe me with their work, the measurement of the refractive index of thallium vapor. The results—or results very similar to them—were published in a paper ["A Measurement of the h/k Ratio through Anomalous Dispersion of Thallium"] and stemmed directly, at least in technique, from Rasetti's doctoral thesis.

Rasetti's influence on Fermi and on the whole group was great, even outside of physics. He read books (fiction and popular science), he traveled to remote places, he collected insects, he ate special foods, and so on. By subtly extolling his own readings or activities he spurred imitation. We called him the "revered master" (*venerato maestro*) in a joking way which had more than a grain of truth in it.

A comic reflection on the community of life and intensity of involvement of the group was that everyone adopted a peculiar voice and accent. Both Fermi and Rasetti had developed a deep voice and a slow, strangely modulated cadence that inadvertently was copied by all of their friends. It was said that one of them, while traveling by railroad, struck up a conversation with another passenger and was very surprised when he was asked if he was a physicist in Rome. He inquired how his companion had guessed this, and the reply was, "from your way of speaking."

The seat of all this activity was the old physics laboratory of the University of Rome in Via Panisperna 89A. . . . I believe that everybody who ever worked there kept an affectionate regard for the old place, and had poetic feelings about it. . . .

Neighboring quarters were occupied by Professor G. C. Trabacchi, who was the chief physicist at the Health Department (Sanità Pubblica). He had an excellent supply of instruments and materials which he generously lent whenever we needed them, a fact that earned him the nickname of "divine providence."

Discovery and the Unforeseen: A Happy Combination of Blunders

From what we have learned so far, it seems clear that the ways through which one arrives at scientific discovery can be very different. Scientific knowledge is a human activity that begins in a comparison with the real. If it is true that scientific activity requires very precise methodological elements, it is also evident that the experience of the scientist—that is, of the person who lives and works in this sphere—cannot be reduced to a scheme or a procedure. The majority of scientists probably sympathize with the irony with which Fermi refers in this passage to the so-called scientific method.

Enrico Fermi[31]

One can go back to the books on method (I doubt whether many physicists actually do this) where it will be learned that one must take experimental data, collect experimental data, organize experimental data, begin to make working hypotheses, try to correlate, and so on, until eventually a pattern springs to life and one has only to pick out the results. Perhaps the traditional scientific method of the textbooks may be the best guide, in the lack of anything better. ✺

Among the factors that contribute most to demolishing a rigid acceptance of the scientific method is the incidence of sheer chance in discovery. We have already cited situations in which an imponderable component appears in the discovery, but sometimes chance and the unforeseen are literally the protagonists. This is certainly not an incitement to methodological anarchy. In fact, a chance event, something unforeseen, can be recognized and made the most of only if it is received within a context of attention, precision, and method. "Chance favors only those who know how to court it" (Charles Nicolle). A flower blown by the wind through the window of a room in complete chaos is not easy to see and is not a novelty; it simply increases (imperceptibly) the disorder. It is different if the flower ends up in a room in which things have a place and a meaning.

This is what, for example, happened to Oersted and Faraday in conceiving the bond between electricity and magnetism, and to John Rayleigh in the discovery of inert gases.

Hans Christian Oersted, Michael Faraday[32]

The age of "big science" began when England engaged in the construction of the most powerful electric battery in the world, which Humphrey Davy had adopted to isolate sodium and potassium, in this way giving life to a new discipline, electrochemistry.

Imagine a lecture on chemistry in Denmark twenty years later. Hans Christian Oersted is explaining electricity and magnetism to a class. On the table of experiments, wires, compasses, batteries, and magnets are spread out in disorder. By sheer chance, Oersted notes that an electrical current makes the needle of a compass near to it move. This chance observation is followed by a series of accurate experiments. The one in which Oersted happened to involve himself is the first direct link between electricity and magnetism, which is said to have led Ampère and his French colleagues to formulate an elegant—and apparently complete—theory of electromagnetism.

The scene changes: ten years have passed and we are in London, in Faraday's laboratory. Given that electricity produces magnetic effects, Faraday asks himself whether magnetism can produce electricity. He passes an electric current through a wire wound around an iron ring, in this way producing a strong magnetic field in the iron. He then winds a second wire around the ring and connects it to a galvanometer, a sensitive detector of electricity. If magnetism were capable of producing electricity, a current should run through the second wire. But this does not work. For a moment, the needle of the galvanometer does not move during the passage of the current but jumps briefly when it is activated or stopped. Faraday notes this leap and does not understand its significance: these are the magnetic fields which produce electricity. Once again curiosity and perseverance have revealed a law of nature: the principle of electromagnetic induction.

Faraday described his discovery in the course of his famous lectures to the Royal Institution. And he relates that when someone asked him what use his researches would serve, on one occasion he replied: "I do not know. But sooner or later the government will put a tax on it." Not long afterward, Faraday's creation made possible the production of electricity through the dynamo and hence the development of the electric motor. Since then our life has never been the same, and the English government has in effect put a tax on electricity.

John W. S. Rayleigh[33]

The discovery of inert gas was even more fortuitous. When chemists learned how to measure the atomic weight of the elements, they arrived at results curiously close to whole numbers. William Prout hypothesized that all the atoms would be composed of hydrogen atoms, but toward the end of the 1990s the so-called Prout's law proved false: the atomic weights could be close to whole numbers but were never precisely whole numbers. Even the atoms of oxygen continued to appear sixteen times heavier than those of hydrogen.

To discover the atomic weight of oxygen, Lord Rayleigh decided to measure its density exactly and the result, as foreseen, was not precisely 16. Having performed this diverting if not particularly important task, Rayleigh dedicated himself to measuring the density of nitrogen, whose atomic weight was already known not to correspond to a whole number. An attentive experimenter, he weighed two different samples of nitrogen, one a product of removing oxygen and aqueous vapor from air, the other obtained by the decomposition of ammonia. And he was amazed when the two samples produced different results.

Was there perhaps an unknown contamination that made one of the two samples heavier and the other lighter? Rayleigh enlisted the help of the chemist Ramsay, and together they discovered a new element present in the air, argon. Other inert gases were successively discovered: neon, krypton, xenon, and, ten years later, radon. Not only had chemists not known the 1 percent of the substances that compose air, but they had to take account of an entire new column in the periodic table: chemical elements almost without chemical properties. And all this was because of Rayleigh's insatiable curiosity.

The most clamorous and, we can say, the most ironic way in which nature can make itself known is to exploit our mistakes. Here is the honest and humorous "confession" of one of the protagonists in the events—about which there is something incredible—culminating in the discovery of "radio novae."

Campbell M. Wade[34]

In the spring of 1970, the Green Bank interferometer was taken off the air and converted to operate simultaneously on wavelengths of 11 and 3.8 cm. Bob

Hjellming and I had been thinking about the problem of stellar radio emission, and, by some reasoning, which at the time we thought to be rather clever, we had concluded that red supergiants offered the best chance of being detectable at these wavelengths. To our amazement and gratification, we were assigned the first three weeks of time on the new interferometer system to look for stellar radiation. This of course reflected NEAO's experience that three weeks were usually needed to make any new system work properly; Hjellming and Wade could debug the beast for the benefit of others. As it happened, however, the thing worked perfectly from the first day. We had a heavy observing list of the red supergiants that our exceptional powers of insight had told us to look at. We also had a number of stars that Bob called "wild cards"—stars of other types that might possibly be detectable. These were to be used as fillers when there were no red supergiants around to fall before our assault.

For the first two weeks we looked at red supergiants all over the place. We even detected one, which we now realize was quite a fluke. That was Antares. Still, we were not doing very well and our hopes of a Nobel Prize were fading, perhaps because we did not have Jocelyn Bell working for us.[35] So we tried some "wild cards." We split the work by having one of us conduct the observing in Green Bank while the other did the dirty work of data reduction in Charlottesville, alternating weekly. It happened that I was in Charlottesville when I got a call from Bob; he had put in one of our "wild cards," and this one actually looked good. It was Nova Herculis 1934, the brightest nova of the century. It was the only normal nova in our list of "wild cards." It was so strong that it could be seen on the monitor in the control room, and the phase was holding steady. This was the best news we had had since going on the air, so we decided to try another nova.

The second brightest nova of the century was of course Nova Aquilae 1918. Since it was above the horizon at the time, we went for it immediately. We had to face the problem that the coordinates we had were for 1900, while the interferometer required 1950 coordinates. We had therefore to go through the freshman astronomy exercise of precessing the position of 1950. Several phone calls later, we finally agreed on the minutes and seconds. Bob immediately put the interferometer onto the new position. In a few minutes he called back, saying, "There's a signal there, but it's weaker." Weaker, but again the phase was steady, so the source was close to the specified position. This was fun! Let's look at another one!

The third brightest of the century was Nova Persei 1901. It too was above the horizon, so we went once more through the dreary exercise of precessing to 1950. Once again it took several phone calls to agree on the result. Bob put the interferometer onto Nova Persei, and after what seemed to me a long time he called to say that this time he could see no signal. Still, a success rate of two out of three was quite a change from what we had been experiencing with the red supergiants. So we altered our observing strategy completely. We looked at novae—old novae, new novae, slow novae, fast novae, one-shot novae, repeating novae, etc. We were very busy that last week on the air. We actually picked up a couple of novae that we subsequently got quite a few papers out of, Nova Delphini 1967 and Nova Serpentis 1970. We came home happy and content.

It was clear that the best way to prove that the signals were in fact from the novae was by positional coincidence. Our radio positions were good to an arc second, but we needed better optical positions. So we approached Larry Frederick, who ran a pretty fair astrometry shop over at the University of Virginia, and he agreed to provide good optical coordinates. To help him find the right constellations, I supplied him with a list of the positions we had fed into the interferometer.

I suppose you wonder where the serendipity in this is, since our success was clearly the result of insight and good judgment. I really don't know how to describe things from here on! Anyway, I got a somewhat agitated telephone call from Larry a short time afterwards, asking when we were planning to publish. Seems he had found discrepancies in a couple of our positions. . . .

Firstly, the declination we had used for Nova Herculis was wrong by exactly three degrees.[36] It hurts to have to stand up in front of people and admit this! Why the error? Well, each observation on the interferometer was controlled by a punched card. I had prepared a card for Nova Herculis, many days in advance, and I must have struck a key in the wrong row (the digit keys were grouped by threes). It was my silly blunder. The right ascension was all right, but you sort of have to get both coordinates right. . . .

G. Westerhout: That's why fan beams are useful![37]

Good point! Anyway, subsequent investigation showed that this "Nova Herculis" was in fact in the Parkes catalog. No wonder it gave good fringes. OK, that's fine, true egg on my face, but at least the blunder pointed us in a new direction.

Now about that error of precisely one hour[38] in the right ascension of Nova Aquilae . . . You don't believe me, do you? But that's the way it happened! Bob Hjellming doesn't make mistakes, but I think, Bob, it is fair to say you were the victim of circumstances. Bob was the only guy who was leaving fingerprints on the key punch at that stage, and it will be to his everlasting credit that the minutes and seconds were exactly right!

Of course, nothing was seen at the position of Nova Persei, for which we had done everything correctly. At least we were right about Nova Delphini and Nova Serpentis—we did get real papers out of those!

Thus it was a happy combination of blunders that led us to find a new class of radio source. When you can't do it any other way, that's how you have to do it! Still, it hurts; if we had been undergraduates, our professors would have suggested that we transfer into a field more appropriate to our intellectual capacities, perhaps physical education.

Dave Heeschen, then the NRAO Director, was pleased with our discovery, although we waited for a day when he was in a good mood to confess the true circumstances. Whereupon he did something quite out of character—he said a naughty word!

Well, the confession is made. I feel clean again, and I will return to my seat.

It seems impossible, but even a lapse can be the expedient through which a new idea makes its way into the mind of a brilliant man. And in the case of Gell-Mann, this was even the solution to the problem of the behavior of so-called strange particles.

Murray Gell-Mann[39]

It has been my pleasure and good fortune to come up with a few useful ideas in elementary particle theory, not of course in a class with Einstein's, but interesting enough to give me some personal experience of the act of creation as it applies to theoretical science.

One example, from very early in my career, will suffice as an illustration. In 1952, when I joined the faculty of the University of Chicago, I tried to explain the behavior of the new "strange particles," so called because they were copiously produced as though strongly interacting and yet they decayed slowly as though weakly interacting. (Here "slowly" means a half-life of something like a ten billionth of a second; a normal rate of decay of a strongly interacting particle state would correspond to a half-life more like a trillionth of a trillionth of a second, roughly the time it takes light to cross such a particle.)

I surmised correctly that the strong interaction, responsible for the copious production of the strange particles, was prevented by some law from inducing the decay, which was then forced to proceed slowly by means of the weak interaction. But what was the law? Physicists had long speculated about conservation by the strong interaction of a quantity called isotopic spin[40] I, which can have values 0, 1/2, 1, 3/2, 2, 5/2, and so on. Experimental evidence in favor of the idea was being gathered at that time by a group of physicists down the hall, led by Enrico Fermi, and I decided to see if the conversation of isotopic spin could be the law in question.

The conventional wisdom was that nuclear (strongly interacting) particle states that are fermions like the neutron and proton would have to have values of I equal to 1/2 or 3/2 or 5/2, and so on, following the example of the neutron and proton, which have I = 1/2. (The idea was reinforced by the fact that fermions must have spin angular momentum equal to 1/2 or 3/2 or 5/2, and so on.) Likewise it was believed that the bosonic strongly interacting particles, the mesons, would have to have I = 0 or 1 or 2, and so forth, like the known meson, the pion, which was I = 1. (Again the parallel with spin angular momentum, which must be a whole number for a boson, strengthened belief in the received idea.)

One set of strange particles (now called sigma and lambda particles) consists of strongly interacting fermions decaying slowly into pion (I = 1) plus neutron or proton (I = 1/2). I thought of assigning these strange particles isotopic spin I = 5/2, which would keep the strong interaction from inducing the decay. But that notion failed to work because electromagnetic effects such as the emission of a photon could change I by one unit and thus evade the law that would otherwise forbid rapid decay. I was invited to talk at the Institute for Advanced Study in Princeton on my idea and why it didn't succeed. In discussing the sigma and lambda particles, I was going to say "Suppose they have I = 5/2, so that the strong interaction cannot induce their decay" and then show how electromagnetism would wreck the argument by changing I = 5/2 into I = 3/2, a value that would permit the decay in question to proceed rapidly by means of the strong interaction.

By a slip of the tongue I said "I = 1" instead of "I = 5/2." Immediately I stopped dead, realizing that I = 1 would do the job. Electromagnetism could not change I = 1 into I = 3/2 or 1/2, and so the behavior of the strange particles could now be explained after all by means of conservation of I.

But what about the alleged rule that fermionic strongly interacting particle states had to have values of I like 1/2 or 3/2 or 5/2? I realized instantly that the rule was merely a superstition; there was no real need for it. It was unnecessary intellectual baggage that had come along with the useful concept of isotopic spin I, and the time had come to get rid of it. Then isotopic spin could have wider applications than before.

The explanation of strange particle decay that arose through that slip of the tongue proved to be correct. Today, we have a deeper understanding of the explanation and a correspondingly simpler way of stating it: the strange particle states differ from more familiar ones such as neutron or proton or pions by having at least one s or "strange" quark in place of a up or down quark. Only the weak interaction can convert one flavor of quark into another, and that process happens slowly. ✺

Finally we record the incredible sequence of fortuitous events that made possible the discovery of penicillin. The sequence is so improbable and delicate that unlike other chance discoveries (all of such a kind that it would be possible to imagine that someone else could have arrived at the same discovery), a second chance would not in fact have been probable.

Alexander Fleming[41]

Such, then, is what I conceive to be the background to the discovery of penicillin [the identification by a young microbiologist of a mould of the penicillium family in a culture left on the bench by Fleming]. An accidental observation it is true, but what an accident, depending as it did on a whole series of apparently unrelated events. The choice of Fleming to write a chapter in a book; the publication of a paper in a scientific journal that prompted him to enquire further; lectures by a Dutch physician that led to the appointment of a mycologist; his working in a laboratory directly beneath that of Fleming; his having the good fortune to isolate a powerful penicillin-producing strain of the mould; his having inadequate apparatus so that the atmosphere became loaded with spores; the high probability that Fleming either forgot to incubate his culture plate or purposely omitted to do so; the fact that Fleming's own laboratory was peculiarly sensitive to outside temperatures; that a cold spell came at a time of the year which is usually unsuitable for the discovery; the visit to Fleming by Pryce that led the former to look again at a plate he had already inspected and discarded; and its having escaped destruction because of entirely inadequate methods for the disposal of used culture plates. All these events, acting in concert, brought to Fleming's notice a phenomenon that cannot, even now, be reproduced unless the conditions in which the experiment is carried out are exactly right. Had only one link in this chain been broken, Fleming would have missed his opportunity.

And if, as Ehrlich used to say, scientific discovery depends partly on *Geld* or money, partly on *Geduld* or patience, partly on *Geschick* or brains and partly on *Glück* or luck, it was the last of them that was almost entirely responsible for the discovery of penicillin. It was, surely, the supreme example in all scientific history, of the part that luck may play in the advancement of knowledge.

Discovery and Gratitude: As in a Rembrandt Picture

There is an aspect of "excess," of "superabundance," in the event of discovery incommensurable with the investment of energy and decisions made, however great these may have been. "The one who has experienced even once in life the pleasure of scientific creation will never forget it" (Pëtr Kropotkin). When a scientist perceives a sign of something new emerging in his research, he notes that reality is responding: it is as if reality, conquered by our efforts, finally concedes something of itself.

The moment of discovery is thus always accompanied by an experience of gratitude, of joy. Claude Bernard has written that "the joy of discovery is certainly the most lively that the mind of man can experience." If the phenomenon of discovery were a due outcome, necessitated by the course of our knowledge, this joy would be inexplicable.

Amazement at discovery is well depicted by the view of someone who has witnessed a unique event, as in the case of the collision of the comet Shoemaker-Levy with the planet Jupiter.

Mario Livio[42]

In July 1994 we had the luck of witnessing directly the rare occasion of an impact of a comet onto a planet. Comet Shoemaker–Levy 9 was broken into two dozen fragments while in orbit around Jupiter, and all of these fragments impacted onto Jupiter's atmosphere in mid July. Every impact produced a rising plume similar to a nuclear mushroom cloud, and the "scars" produced at the impact sites could be seen on Jupiter's atmosphere for months after the collisions. I still remember vividly the evening on which the first impact occurred. Gene and Carolyn Shoemaker and David Levy, who first discovered the comet, were at the Space Telescope Science Institute, as were astronomer Hal Weaver, who observed the "string of pearls," as the chain of orbiting fragments was called, and many other planetary scientists. Heidi Hammel from MIT was granted Hubble Space Telescope time to observe the collision that was about to occur, but at that point it was not clear at all whether anything of interest would be seen, since theoretical models showed that unless the fragments were relatively large, the observable effects would be miniscule. The Shoemakers and Levy were holding a press conference in the institute's auditorium, while Heidi, Hal, and other astronomers (myself included) gathered around a computer screen in our operations room to see the first images as they would be transmitted from the telescope. Suddenly, a tiny bright dot appeared above Jupiter's horizon. Heidi asked: "Does anybody know if a moon should appear here?" and a few people started to check for that. However, a short time later it became clear that this was not a moon. A bright plume became clearly visible above the horizon. It was unbelievably beautiful. Somebody took a picture of all of us crowded around the computer screen, with a look of absolute amazement on our faces. It is a fantastic picture of the awe of discovery. The first time I saw that picture I immediately remarked that it is incredibly reminiscent of Rembrandt's painting *The Anatomy Lesson of Dr. Tulip*. In that painting, too, Rembrandt concentrates not on the operation itself, but rather on the astonished, eager-to-learn faces of the anatomy students. ✺

The event of a discovery establishes such a deep and all-absorbing relationship with reality that everything of that moment remains in the memory of the discoverer. As Charles Darwin recalls, "I can remember the very spot in the road, whilst in my carriage, when to my joy the solution occurred to me."[43] Arriving at a result of fundamental usefulness for the world further increases the gratitude of the protagonist. Edward Jenner wrote, "The joy I felt at the prospect before me of being the instrument destined to take away from the world one of its greatest calamities . . . was so excessive that I sometimes found myself in a kind of reverie."[44]

Enthusiasm for the new is at one with the desire to share it, as Beveridge has observed: "The discoverer has an urge to share his joy with his colleagues and usually rushes into a friend's laboratory to recount the event and have him come and see the results."[45]

The same emotion in the face of mystery unites two giants of science, belonging to two quite different historical eras: Heisenberg, having verified the validity of the principle of the conservation in quantum physics, and Kepler, at grips with his famous laws on the motion of the planets.

Werner Heisenberg[46]

Within a few days . . . , it had become clear to me what precisely had to take the place of the Bohr–Sommerfeld quantum conditions in an atomic physics working with none but observable magnitudes. It also became obvious that with this additional assumption I had introduced a crucial restriction in the theory. Then I noticed that there was no guarantee that the new mathematical scheme could be put into operation without contradictions. . . . It was completely uncertain whether the principle of the conservation of energy would still apply. . . .

. . . I concentrated on demonstrating that the conservation laws held, and one evening I reached the point where I was ready to determine the individual terms in the energy table, or, as we put it today, in the energy matrix, by what would now be considered an extremely clumsy series of calculations. When the first terms seemed to accord with the energy principle, I became rather excited, and I began to make countless arithmetical errors. As a result, it was almost three o'clock in the morning before the final result of my computations lay before me. The energy principle had held for all the terms, and I could no longer doubt the mathematical consistency and coherence of the kind of quantum mechanics to which my calculations pointed. At first, I was deeply alarmed. I had the feeling that, through the surface of atomic phenomena, I was looking at a strangely beautiful interior, and felt almost giddy at the thought that I now had to probe this wealth of mathematical structures nature had so generously spread out before me. I was far too excited to sleep, and so as a new day dawned, I made for the southern tip of the island, where I had been longing to climb a rock jutting out into the sea. . . . I now did so without too much trouble, and waited for the sun to rise. ✺

Johannes Kepler[47]

With this small work I have proposed to demonstrate, dear reader, that in the construction of the world and the disposition of the heavens God the Best and Greatest observed the five solid rules which have been celebrated so much from the time of Pythagoras and Plato and which dispose number, proportions and movements of the heavenly things according to the properties of these bodies . . . The three questions were principally devoted to investigating the reason why they are thus and not otherwise: number, extension and the period of the orbs. The miraculous harmony of immobile things—the sun, the fixed stars and the space which correspond to the Trinity of God the Father, God the Son and the Holy Spirit—encouraged me in this attempt. I had no doubt that moving things would have revealed to me the same harmony as immobile things. Tackling the problem from a numerical perspective would be considered if an orb were not twice, three times and four times another. . . .

I finally succeeded in arriving at that solution as by chance and remembered that it had befallen me by divine will to discover fortuitously what I had not succeeded in determining with such effort.

For those who experience it, the emotion of discovery is great, even when the object of the discovery, seen from outside, seems modest. The naturalist Alfred Wallace recalls his state of mind when he succeeded in discovering a new kind of butterfly: "My heart began to beat violently, the blood rushed to my head, and I felt like fainting . . . so great was the excitement produced by what will appear to most people a very inadequate cause."[48]

Gratitude for the step taken is not only linked to satisfaction at having done something important, but indicates a deeper experience: every discovery, small or great, evokes the perception of a mysterious correspondence that links reality to the human "I." Allowing itself to be discovered and understood, the physical world shows that it has been made for the "I," and the human person confirms its vocation of being destined for a relationship with all things, with the universe. In the experience of discovery, it is as if, for a brief moment, the physical appearances of things, too, allow us to see another truer and ineffable face of reality: the secret friendship of everything with the human person.

Discovery and Certainty: Courage to Go through the Mists

Often, at the moment of their first enunciation, discoveries are not as self-evident as they will be in future, and they are almost never universally shared by the scientific community. It is only with the passage of time that their trustworthiness and their effective scope become clear. Above all, when radical discoveries have profound consequences in the way of thinking about a phenomenon or a whole sector of science, they encounter hesitation and opposition.

Influential parts of the scientific community will tend to stress those experimental data and observations that tend to contradict and put in doubt the new results. The data may suggest a new discovery in a persuasive, but rarely in an inevitable and incontrovertible, way. Thus, small or great, courage is needed to affirm with clarity something really new in the face of everyone. A human subject has to give a summary judgment from a situation that has its clear and obscure aspects, its open points. That is the risk run by someone who can open the way to what in time can become a certainty.

It is to this courage, this conviction, that recognition of the historical merit of the discovery is closely bound. Cosmologist Edward Kolb here discusses the emblematic case of Edwin Hubble, who is credited with the discovery of the expansion of the cosmos.

Edwin Hubble[49]

Why does Hubble get the credit? Why not Slipher, Lundmark, Wirtz, or any number of other astronomers who were so close to discovering the expansion of the universe? What about Friedmann, de Sitter, or Weyl, all of whom to some extent predicted the expansion and the red shift? Is it fair to say that Hubble discovered the expansion of the universe? What did Hubble do that the others did not?

In my opinion, Hubble justifiably deserves credit for the discovery of the expansion of the universe. One reason is that Hubble established distances to the galaxies, and only if the distances are known can one say for sure that the red shift increases in proportion to the distance. Another reason is that his paper contains something lacking in the others: a clear and concise statement of the result, and demonstration of a strong conviction that it is true. The message is stated in the title of the paper and is made clear throughout the paper with no ifs, ands, or buts. While others cloaked the possibility of the expanding universe in threads of complexity, or hid behind the tentativeness of "uncertain data," Hubble stood up with an air of confidence and said, "This is the way it is." If someone really knows what he is doing, and is confident in the result, he doesn't bury the result in a footnote or hide it in an inconspicuous paper.

Shortly before Andrei Sakharov's death, I attended a conference honoring his scientific accomplishments. Although notoriety in his later years was due to his brave political stance for human rights, throughout his lifetime Sakharov made many important contributions to physics and cosmology.

Among the many physicists at the meeting recounting Sakharov's discoveries was one who made the surprising claim that in a footnote to an otherwise unknown paper, Sakharov had proposed a theory that a decade later proved to be the correct theory of the forces responsible for blinding quarks inside neutrons and protons.

There is really no need to look through Sakharov's footnotes to find evidence of his remarkable insight as a physicist. Furthermore, I am convinced that he must not have understood the implications of what he said in the footnote, or perhaps he really didn't believe it, because it is inconceivable to me that anyone would make a discovery of that magnitude and hide it in a footnote.

Hubble didn't hide his result in a footnote, but stuck his neck out. Indeed, to claim discovery of the expansion of the universe was a risky statement at the time—the data were not overwhelming. If we plot the recessional velocity versus distance as Hubble did, it is not totally obvious that it is a straight line. In fact, it is not obvious at all.

Anyone who has taught a high school or introductory college physics course knows that no matter what the data look like, a student invariably will draw a straight line through the points (even if the answer isn't supposed to be a straight line). Looking at the data that Hubble had to work with, we can see that it is not clear that a straight line should be drawn through the points. Part of the reason for the poor agreement is that there is a secondary effect that spreads the points around. Just as Galileo had to overlook the fact that a feather will not drop at the same rate as a bowling ball because of the secondary effect of air friction, part of Hubble's insight was to overlook the fact that his expansion law isn't exact, but it is an approximation (and not a very good one for nearby galaxies), because of the secondary effect of the motions of galaxies due to the gravitational effect of neighboring galaxies.

In fact, some of the nearby galaxies, like Andromeda, are actually approaching us. We now know that in addition to the recessional velocity predicted from Hubble's law, all galaxies have small random velocities that either add to or subtract from the Hubble velocity. When we measure the red shift of a galaxy, we measure a part due to the expansion of the universe, given by Hubble's law, and a part contributed by the random motions. The magnitude of the random velocities is about the same for every galaxy, while the recessional velocity according to Hubble's law increases with distance. So the random velocities can overwhelm the Hubble velocity for nearby galaxies, but they are an insignificant fraction of the total velocity of very distant galaxies. The further we look, the more accurate Hubble's law becomes. But the random velocities clouded the issue for the nearby galaxies Hubble knew about in 1929. In fact, when astronomers display a "modern" Hubble diagram, they don't even bother putting Hubble's original data on the graph. Now we know that if we extend the graph drawn by Hubble by looking at galaxies beyond his reach at the time of his first paper, the secondary effects are unimportant. But Hubble couldn't be sure.

It required no small amount of courage for Hubble to state his law. At the front, in the fog of physics on the raw edge of ignorance, the answers are shrouded in mist and are not as clear as they later become.

Certainty 5

What was lost in the modern age was not of course the capacity for truth, for reality, for faith or the inevitable concomitant acceptance of the testimony of the senses and reason, but the certainty which used to accompany it. **HANNAH ARENDT**

When you have at last arrived at certainty, your joy is one of the greatest that can be felt by a human soul. **LOUIS PASTEUR**

Wisdom is the taste of things as they are. Science is to go through the causes, the effects, and the certain signs, from the taste of something to the knowledge of other things as they are. **TOMMASO CAMPANELLA**

According to a widespread point of view, through science it is impossible to arrive at any positive certainty in respect of reality: researchers, it is said, do not put reality to the test but only the models of reality that they invent from time to time. A certain model or scientific hypothesis can never be judged "true": even after thousands of experiments that "corroborate" the hypothesis, scientists have to admit the possibility that the umpteenth experiment will give a result that contradicts it and condemns it to be discarded as "false." Nothing positive can be said, nothing certain about "how things are." At best, it will be possible to produce now and then a certainty of a negative kind: when an observation contradicts our hypothesis we can assert with certainty that "things are not like this." Karl Popper has expressed with precision this conception that to a large degree still dominates the scene: "The theories are our inventions, our ideas: they do not impose themselves on us but are our instruments of thought that we have made by ourselves. But some of our theories can clash with reality and when they do, then we know that there is a reality, that there exists something to remind us that our ideas can be mistaken."[1] According to this approach, reality is experienced only to the degree that it can contradict our thoughts about it.

In part this way of thinking picks up an authentic aspect of the mode of advance in science, perhaps the most mechanical one. However, it does not seem sufficient to account for all the riches of the experience of knowledge that we have through science: it does not take account of the fact that the experience of certainty is continually present and is indispensable to the dynamic of the knowledge of every researcher. Today the "weak" conception of knowledge seems to have moved from the thought of the elite to the general mentality: to speak of certainty today is not in fashion. In the West it is expected from any well-educated person, all the more if they happen to be "scientists," to qualify any positive expressions or judgments on reality (including the affirmation that reality itself exists) with a touch of doubt. In our times, the more people belong to the intellectual sphere, the more they seem to "strive not to believe in what they believe," as Charles Péguy put it. Thus, it is not "intellectually correct" to say that "the sky is blue!" and that is that; there is a need to add that it is blue only in certain conditions, which will not always prevail, and that in any case to say "blue" is only a convention and, in any case,we cannot verify precisely what each of us thinks of when we use the word "blue," and so on. All these specifications of course have their own value and justification in the appropriate circumstances, but they must not confuse us to the point of losing sight of the evident, notable, and beautiful fact that "the sky is blue"!

In fact, it is clear that in living, and certainly also by doing scientific research, it is all the more necessary to put one's feet on what experience indicates to be solid ground: on the "evidence," as we said in the first chapter. Even if it is rarely admitted, curiosity and the new questions that launch scientific investigation arise out of enthusiasm for what is recognized as certain, rather than putting a shadow of doubt on what is evident. To paraphrase Ernst von Bruecke, it could be said that "certainty is a woman without whom no scientist can live, but all are shy of appearing in public with her." For example, from the evidence of the (interesting) fact that the sky is blue, the question arises: "What is it that makes the sky appear blue?"—by no means a trivial question, which the physicist translates into: "Why is the visible electromagnetic radiation scattered by Earth's atmosphere in such a way that it is dominated by light of a short wavelengths?"—and physics is in a position to try and give an answer.

Certainty plays a role at the beginning of research, but it is also the hope of its destination: scientific knowledge aspires to attain "moments of certainty." These are conclusions of great importance, which have been secured with the force of the facts, the fruits of a long course that researchers of different generations have been able to cover in depth. It is not that scientists cannot say for certain, for example, that biological life is based on DNA, that water is composed of hydrogen and oxygen, that nuclei are made up of protons and neutrons, that there was an age of dinosaurs, that the spiral nebulae are external galaxies. All these statements, which can be taken for granted, are in reality formidable achievements about which we have gained the greatest degree of confidence. Only a few centuries ago, the majority of these affirmations were anything but indisputable, and some of them were not even conceivable. But today no one has any reason to doubt, for example, that the sun is a star. That does not mean that we know everything about the sun; for example, we still don't understand the physical processes that make the outer solar atmosphere, the corona, extremely hot, with temperatures reaching millions of degrees, or we don't quite understand and can't predict the violent phenomena related to solar magnetic activity; and so on. But that does nothing to undermine the achievement of the clear and definitive awareness that we have today about the physical nature of the sun, which is part of the great family of billions of stars that make up the galaxy. It is thanks to science that we have this certainty, and it is a result that says something interesting about our position in the cosmos. Not even the fervid imagination of the ancients was so bold as to suppose that what research teaches us today is an incontrovertible fact: the star that dominates our sky and our life is of the same species as those minuscule points of light suspended in the blackest vault of the nocturnal sky.

It is not reasonable to suppose that in the future an experiment will contradict this conclusion. At a certain point we no longer have a very probable hypothesis but certainty. But what kind of statement is "The sun is a star"? It relates to a "quality" of the object. Every scientist is well aware that there will always be a margin of provisionality (of "uncertainty") in any measurement, in any "quantitative" definition of observed magnitudes and in the approximation with which his models describe reality. But that does not alter the fact that reality is made in a certain way, and that we can really know something of it.

The great success of the experimental method is bound up with the identification of measurable quantities, with the translation of our statement in mathematical language and with the rigor of procedures. But perhaps it can also be said that every quantitative step on the scientific way ultimately aspires to bring out a certain "quality" of the object. And the scientific method, with its step-by-step advance, is a way that sometimes allows researchers to actually grasp what they are passionately researching. The particle physicist thinks up delicate experiments and accumulates new measurements because he is interested in understanding the nature of an elementary particle (e.g., whether it is a wave, a corpuscle, or an irreducible combination of the two); the astronomer plans new observations to clarify the nature of certain classes of celestial objects—for example, she wants to know the physical mechanism responsible for their emission of energy; the cosmologist tries to make observations at the limits of technology to decide whether the universe is static or evolving; the chemist is interested in understanding the structure of a molecule and how and why its behavior differentiates it from other similar molecules. Scientists are particularly enthusiastic when they succeed in bringing to light *qualitative* characteristics of what they are studying: existence, origin, evolution, structure, function, physical nature, relationship with the universe. The description of these fundamental features of the object and, in general, of the physical world, constitutes a great contribution that scientific knowledge offers to our awareness of the world in which we live. And it is particularly in respect of these qualitative properties that in time, with prudence and humility, it is sometimes given to us to attain the summit of certainty.

Certainty and Reality: So, This Is Nature. Who Would Have Guessed It?

Much philosophy of science has tried to argue that concepts such as truth and certainty are definitively outmoded, in that our knowledge of the world is determined *a priori* by linguistic procedures and mental functions. Thus, attempts have been made to describe scientific theories as our more or less arbitrary projections on reality, the fruit of social conditioning, capable of organizing a series of pieces of information according to a scheme of our making. This position, however, is much more widespread among philosophers of science than among scientists. For those who are personally engaged in the battle of research, it is evident that the characteristics of the physical world are as they are and are not quite at the mercy of our interpretation. The victorious scientific theories and hypotheses are anything but the arbitrary inventions that we project on reality, but features that indicate that "this is really the case."

John Polkinghorne[2]

Philosophers of science have latterly been busy explaining that science is about correlating phenomena or acquiring the power to manipulate them. They stress the theory-laden character of our pictures of the world and the extent to which scientists are said to be influenced in their thinking by the social factor of the spirit of the age. Such accounts cast doubt on whether an understanding of reality is to be conceived of as the primary goal of science or the actual nature of its achievement. These comments from the touchline may well contain points of value about the scientific game. They should not, however, cause us to neglect the observations of those who are actually players. The overwhelming impression of the participants is that they are investigating the way things are. Discovery is the name of the game. The pay-off for the rigours and longueurs of scientific research is the consequent gain in understanding of the way the world is constructed. Contemplating the sweep of the development of some field of science can only reinforce that feeling.

Consider, for example, our understanding of electricity and magnetism and the nature of light. In the nineteenth century, first Thomas Young demonstrated the wave character of light; then Faraday's brilliant experimental researches revealed the interlocking nature of electricity and magnetism; finally the theoretical genius of Maxwell produced an understanding of the electromagnetic field whose oscillations were identifiable with Young's light waves. It all constituted a splendid achievement. Nature, however, proved more subtle than even Maxwell had imagined. The beginning of this century produced phenomena which equally emphatically showed that light was made up of tiny particles. . . . The resulting wave/particle dilemma was resolved by Dirac in 1928 when he invented quantum field theory, a formalism which succeeds in combining waves and particles without a trace of paradox. Later developments in quantum electrodynamics (as the theory of interaction of light and electrons is called) have led to the calculation of effects, such as the Lamb shift in hydrogen,[3] which agree with experiment to the limits of available accuracy of a few parts per million. Can one doubt that such a tale is one of a tightening grasp of an actual reality? Of course there is an unusually strong element of corrigibility in this particular story. Quantum electrodynamics contains features completely contrary to the expectations which any nineteenth-century physicist could have entertained. Nevertheless there is also considerable continuity, with the concepts of wave and field playing vital roles throughout. The controlling element in this long development was not the ingenuity of men nor the pressure of society but the nature of the world as it was revealed to increasingly thorough investigation.

Considerations like these make scientists feel that they are right to take a philosophically realist view of the results of their researches; to suppose that they are finding out the way things are.

In their actions, scientists tend to assume a realistic position, which takes account both of the fascinating presence of the world "outside," waiting like a girl who makes one smile, and of the human attempt to describe that world in scientific terms, with all the inevitable incompleteness and provisional nature of such description. But even in the limit of this approximation, what reveals itself is a "real" aspect of the world. It is difficult for those with the experience of research to be in substantial disagreement with John Polkinghorne about the typical way in which the scientist relates to reality, and even if they disagree in theory, probably their mode of operating will be remarkably close.

John Polkinghorne[4]

It is clearly not possible to claim that science establishes truth, pure and simple. Entry into some hitherto unexplored regime (of higher energy or shorter distance or whatever) is always liable to reveal new and surprising phenomena that will call for conceptual modification or even a totally new way of thinking. In that sense, the conclusions of science are necessarily provisional. Indeed, it is the possibility of finding the unexpected around the next experimental corner that motivates the expensive exploration of artificially created regimes (such as are produced in high energy accelerators), far beyond what is accessible to us through natural encounter with the physical world. Yet, when we consider a regime that has been well winnowed by the flail of experiment and the sieve of theory, then we do not expect to have to change our ideas radically about what is going on. Newton did not say the last word about the solar system—Einstein's theory of a general relativity is necessary to explain the fine detail of the behaviour of the planet Mercury—but his theory of gravity is sufficiently close to what is actually the case for us to be able to use it to send a space probe to Mars. If science does not attain absolute truth, surely it can lay claim to verisimilitude. Its established theories give reliable accounts of what is going on in a carefully delimited domain, to specified degrees of detail and accuracy. Scientists are mapmakers of the physical world. No map tells us all that could be said about a particular terrain, but it can faithfully represent the structure present on a certain scale. In the sense of an increasing verisimilitude, of ever better approximations to the truth of the matter, science affords us a tightening grasp of physical reality.

So say I, and almost all other scientists with me, but not so all philosophers. The intertwining of interpretation with experience, together with the underdetermination of theory by experiment, has persuaded many of them that science's encounter with the physical world has about it a degree of elasticity that yields considerable room for explanatory manoeuvre. The theoretical insights of science are then seen as the imposition of a pattern of meaning on a veiled and elusive reality, rather than as reliable inferences from encounter with its actual nature.

The most extreme critics of this kind are those who see science as being largely, or even totally, a social construction. Thus, the sociologist Barry Barnes can propose that "all knowledge generation and cultural growth should be regarded as endlessly dynamic and susceptible to alteration just as is human activity itself, with any actual change or advance a matter of agreement and not necessity." In his view, in the 1970s we did not discover quarks, we simply (unconsciously) agreed to view the world of ambiguous experience in a quark-like way. Physicists have the choice of what experiments are worth doing and how they should interpret them. In consequence, they can mould their encounter with the subatomic world into a shape that pleases their intellectual fancy. Anyone who does not go along with that self-imposed orthodoxy is excluded from the invisible college of scientists. . . .

It is difficult to exaggerate how implausible this account seems to a high energy physicist. Far from the physical world proving to be like clay in our theoretical hands, it displays a diamond-like hardness, resistant to our expectations and imposing upon our minds its idiosyncratic and unanticipated structure. It is an immense struggle to find a theory that is economic and uncontrived and adequate to a wide swathe of experimental investigation. More than twenty years elapsed between Murray Gell-Mann's discovery of the strangeness quantum number and the articulation of the fully developed Standard Model of the quark theory of matter. They were years of continual experimental surprises and ceaseless theoretical struggles to make sense of what was going on. When finally a coherent picture emerged, it had all the feel of discovery and none of the feeling of pleasing construction. "So that's what nature's like—who'd have thought it beforehand!" ✺

The metaphor of the scientist as "cartographer" of nature is effective and precise. Polkinghorne suggests that the scale of the map is analogous to the approximation to the truth that science gradually achieves. And the metaphor can be extended even further. The same territory can be described by successive versions of topographical maps with different projections and made by different techniques. The most recent editions will presumably be increasingly accurate, but the new maps will not necessarily replace all their predecessors immediately. Only occasionally on the appearance of a new edition will it be necessary to correct real "errors" in the old versions. So today we can continue to use the laws of Newtonian mechanics to plan the trajectory of space missions while being aware that they have been "superseded" by Einstein's laws of general relativity; on the other hand, no one today embarks on a transatlantic crossing with the geographical maps of Magellan, just as we do not use epicycles to forecast the positions of the planets in the stellar vault. But just as in science the same object can be studied from different perspectives, so every map necessarily emphasizes certain aspects of what exists in a given territory. The map of an Alpine valley designed by expert excursionists will be rich in details of paths, huts at high altitudes, and the orography of the peaks; it will have different characteristics from a map with all the routes recommended to keen mountain bikers. That does not mean that the two maps are in conflict, nor is one better than the other; both say something true and positive about reality.

It is again Polkinghorne who has recalled that in science the most interesting and decisive experiments are those that make it possible to discriminate with clarity between quantitatively different interpretative scenarios. In fact, this is the dynamic that motivates great projects. In 2009 the CERN Large Hadron Collider (LHC) will make it possible to collide beams of protons of an energy of 14 TeV (14 million million electron volts), a big step forward in respect of energy that today can reach 1 or2 TeV, but this quantitative step is mainly motivated by the possibility of distinguishing between *qualitatively* different scenarios that can be distinguished only at energies beyond a certain threshold. In this case the objective is to verify the existence of the Higgs particle, which has been conjectured as an explanation of the mass of all the other particles. Perhaps in the future the CERN scientists will be able to be as certain of the existence of the Higgs particle as we are now certain of the existence of the electron or neutron, even if the quantitative properties of these particles will always be known with a limited degree of precision. Analogously, an astrophysicist is not greatly interested in knowing whether the distance of a certain star—say, Alkaid of Ursa Major—is 812.24 rather than 812.23 light years away, unless there is a significant physical quality that to be proved requires that precision of measurement and justifies the efforts, including the economic efforts, needed to obtain it.

John Polkinghorne[5]

On the way to the discovery of quarks and gluons, there were crucial moments of insight derived from such critical experiments. One such was the discovery in the late 1960s of what is call deep inelastic scattering. When very high energy electrons are scattered by protons, some of them "bounce back" in a surprising way. The historically minded would have thought of Rutherford and his colleagues in Manchester in 1911. Working at much lower energies, they had detected a similar bouncing back of α-particles when they impinged on a thin gold foil. Rutherford said it was as astonishing as if a 15-inch naval shell had recoiled on impact with a sheet of tissue paper. He went to interpret it as indicating the presence of concentrated positive charge inside the gold atom. In a word, he had discovered the nucleus. It was possible to understand the Stanford electron experiments in a similar fashion, but now the little hard scattering centres proved to be identifiable with the quarks sitting inside the proton. Up to that point it had been possible to think of quarks as being no more than a kind of theoretical toy, a notional device to generate certain patterns in the ordering of matter; thereafter it became clearer and clearer that quarks must be reckoned as a new constituent level in the structure of the physical world. Some people liked that, others did not, but the physicists had been given a nudge by nature that no one could ignore, whatever their predilections. Of course, its recognition depended on interpretation. Matter is not stamped "made of quarks." But the interpretation was both so natural, and so effective in explaining the phenomena, that it could not be gainsaid. The origin of quark theory lies in the physical world and not in the minds of physicists.

It is a fact that the scientific method has been asserted in a very precise historical and cultural context, that of the Christian West. This is not the place to discuss the interesting correlation between the cultural position introduced by Christianity and the emergence of the method of knowledge that today we call "scientific." (See on this topic the excellent works carried out by authors such as Stanely Jaki and Peter Hodgson.) Rather, this comment by Paul Davies emphasizes that whatever the course of its emergence may have been, the fruits of this mode of knowledge relate to aspects, though very selective and particular, of objective reality, of the world as it presents itself to the eyes of the observer.

Paul Davies[6]

The identification of science with European culture has led to accusations of chauvinism. It is sometimes claimed that the so-called success of science is nothing more than the dominance of Western European culture over others. For example, certain scientific theories were banned in communist countries, and some radical feminists still claim that science as we know it is fundamentally male oriented in conceptual structure. The appearance of "feminist" science, "Islamic" science or "Christian" science, and the rejection of scientific values altogether by some critics, may be in part a response to this perceived chauvinism.

It is inevitable that the formulation of science will acquire slants and perspectives that reflect the prejudices of its practitioners. And most scientists have been, until recently, middle class males of European origin. This may provide some grounds for claims of chauvinism. However, although science is a product of European patriarchal society (and there may still be some cultural relativism in the way it is constructed and taught), I contend that the success of science runs far deeper than the special interests of middle class males of European origin. Science really has given us a (partial) understanding of nature, and has led to genuinely new discoveries about the world, discoveries representing true facts that are just as true for other cultural groups as for the scientists. It is simply there, for everybody, and it is almost certain that the Z particle would never have been discovered by a system of thought other than of DNA. Whatever the cultural, social or political reasons, the early scientists of Western Europe came across a way of looking at the world which is remarkably fruitful, and cannot be shrugged aside as a mere cultural construct. No attempt to build a theory of existence that ignores the power of the scientific world view can carry much conviction. ✺

Certainty and Patience:
The Veils of Nature Do Not Fall Suddenly

Certainty comes in time, and calls for a long period of living with the object that is being studied. Reaching the conviction of being on the right road requires patience. The physicist Pierre Duhem has suggested a fine image for the advance of scientific knowledge that combines both the progress of science as a whole and the slow and almost imperceptible clarification of the individual phenomenon.

Pierre Duhem[7]

Anyone who casts a brief glance at waves striking a beach does not see the tide rising; he sees a wave swell, run, uncurl itself, and cover a narrow strip of sand, then withdraw, leaving dry the terrain which it had seemed to conquer; a new wave follows, sometimes going a little farther than the preceding one, but also sometimes not even reaching a sea shell made wet by the former wave. But under this superficial to-and-fro motion, another movement is produced, deeper, slower, imperceptible to the casual observer; it is a progressive movement continuing steadily in the same direction and by virtue of it the sea constantly rises. The toing and froing of the waves is the faithful image of those attempts at explanation which arise only to be crumbled, which advance only to retreat; underneath there continues the slow and constant progress whose flow steadily conquers new lands, and guarantees to physical doctrines the continuity of a tradition. ✺

Rapidly retracing the principal stages and the discoveries of modern physics, one of the main protagonists of the birth of quantum physics, Erwin Schrödinger, observes in perspective how the achievement of the great innovations introduced by quantum mechanics required time and patience.

Erwin Schrödinger[8]

Planck said in 1900 . . . that he could understand the radiation coming from red-hot iron or from a star that emanates white light, as for example the sun, only if this radiation is produced in portions and transmitted from one object to another . . . only in portions. That could not fail to amaze, because this radiation is energy, and energy was in origin an extremely abstract concept, a measurement of the reciprocal action or capacity for action of some very small particles. . . . Five years later Einstein said that energy has a mass and that the mass is energy, in other words that they are the same thing, and this too has remained true to the present day. But now we feel as if a veil is falling from our eyes: our dear old atoms, our particles, are Planck's quanta of energy. The quanta are then carried by other quanta. It makes one dizzy. Here we accept that at the basis there is something fundamental that we do not yet understand. In reality those veils did not fall quickly. They were to take thirty years. And perhaps they have not fallen completely even today.

Certainty and Limits: Exploitation of Success and . . . Failure

Attaining a clear understanding of a certain phenomenon, however limited, remains rare; it is like a small island of terra firma in the vast ocean of the unknown. If it is clear that science can shed some light on the behavior of the physical world, the impression that the unknown ocean that lies beneath what we see and in part understand is immeasurable in depth and extension is even more powerful. A sign of this is the fact that often researchers find themselves having to live with problems the solution to which seems not only distant but impossible. In this situation, even "to accept the company of a good problem," as mathematician Ennio De Giorgi writes, has its aspect of fascination and ultimate positivity. And it is important to mistrust those who, having arrived at results of great importance, delude themselves that "they have found the ultimate theory in which it should be possible to absorb any further research."

Ennio De Giorgi[9]

Often in the applications of mathematics, alongside the "direct" sense of a theorem, i.e., that the hypotheses are true and the thesis is true, it is important to consider the "inverse" significance, i.e., that if the thesis is false, then at least one of the hypotheses is also false. This type of consideration arises all the time when it is said that an experiment "falsifies" or "refutes" a particular theory, in other words when in carrying out the experiment different results are obtained from those predicted by the theory. Without embarking on a discussion in the philosophy of science, which others could develop with greater competence than I, it seems to me that these elementary considerations could help us to understand the philosophical theories of those who say that scientific theories are not verifiable, but are falsifiable. More generally, confronted with the failure of the forecasts made on the basis of particular mathematical theories, it is almost superfluous to say that in life theory and practice are rarely in accord; it is important to ask why a certain mathematical model, however ingenious and brilliant, does not take good account of the course of certain phenomena, or the quantity of errors that have emerged in the survey of the data is too great.

On the other hand, the refutation of a certain mathematical model need not mean a renunciation of all theoretical investigation of certain phenomena; rather, it is a stimulus to look for more adequate models. Immediate success is not to be expected in such research; it is important for those seeking to resolve the most interesting problems also humbly to know how to accept and appreciate the company of a good problem which resists one's attempt to solve it, to recognize that unsolved and solved problems are a sign of the vast richness and complexity of the reality that surrounds us. Basically, true scientists, good teachers, good scientific popularizers, know how to enjoy the thought of these riches; they can learn from the recollection of mistakes made and failed attempts; they can appreciate Shakespeare's words, "There are more things in heaven and earth than are dreamed of in your philosophy." These words are not an invitation to "dream less" but rather to "dream more" if we want to arrive at a broader understanding, even if always very partial, of the reality that surrounds us. They are an invitation to distrust those scientists who, having achieved some brilliant success, are deluded into thinking that they have found the ultimate theory in which it should be possible to absorb any further research.

In this freedom to dream, mathematicians must not stop at the objects which offer an immediate representation of themselves to the senses; they must move freely between "real" and "ideal," "concrete" and "abstract," "visible" and "invisible," "finite" and "infinite," recalling that often the solution of the most concrete problems involves the study of the most abstract problems; for example, the solution of many problems of technology and engineering involves the use of infinitesimal calculus, i.e., the most daring of mathematical concepts, the concept of infinity.

The freedom of mathematicians' imaginations is matched by their duty not only to formulate their own theories in a clear and unequivocal way, to indicate the fundamental axioms with precision, but also to evaluate the logical consequences attentively. If in fact a theory is all the more beautiful and interesting the more rich and varied the series of theorems that can be deduced from its axioms, it loses a good part of its interest when the consequences of the axioms are contradictory. In fact it is enough that a proposition and its negation, or all the propositions and their opposites, can be deduced from the axioms of a theory, and thus that in substance it is possible to deduce everything and the contrary of everything.

. . . I shall not dwell on this question, of which others can speak better than I can; I shall limit myself to observing that in the last analysis the principles of the scientific method are basically principles with the character of wisdom: the humility necessary to accept one's own errors and the limits of one's knowledge, the need to confront oneself with as broad a circle of interlocutors as possible, the intellectual honesty of those who seek to put forward their own ideas with the greatest sincerity and the greatest clarity, admiration at the vast riches of the reality which surrounds us, and trust in the Wisdom which often in an unexpected way comes to meet those who seek with that spirit which the ancients called "philosophia," i.e., love of wisdom. ✺

In their tension with the truth, scientists try to support their own theses, but at the same time are critics of themselves and others. When it is really motivated by the desire to know "how things are," the competition that usually develops between different groups of researchers also contributes to identifying and correcting the mistakes that are inevitably hidden in the folds of one's own ideas and interpretations. This is not a matter of insincerity or of a taste for polemic, but rather a way of expressing a desire for truth.

Robert Pollack[10]

Practicing science is an analytical act and also a creative one. The second barrier to understanding is that scientists' endless rounds of "on the other hand" are often mistaken for an inability to be certain about the meaning of an experiment. It is as though every professor of English were at once a writer of novels and an interpreter–theorist of those very novels. Such people are rare in the humanities and social sciences, but all productive scientists are quite resigned to oscillating between creation and criticism, knowing that public recognition without continued carping from one's peers is useless and empty praise.

The basic problem is that most nonscientists do not have a very clear understanding of the paradox underlying all scientific advances: namely, that scientists love to do experiments that show their colleagues to be wrong. By this adversarial process, science gradually reveals the way nature works. The notion that published science must be free of error, and that error itself indicates sloppy thinking or fraudulent intent, is misguided. Bystanders often misunderstand the place of error in science and imagine that scientists who override one another's findings are in some way not entirely serious about their work or that no scientific statement can be true if any one is false. ✺

The capacity to recognize one's own mistakes is essential to the way toward certainty, and here scientific knowledge is no exception. When a false step is recognized as such and identified in the context of a clear tension with the truth, an obstacle can become an opportunity. There are errors that in some way are a prelude to the truth. René Thom, the mathematical physicist and founder of catastrophe theory, has written: "The truth is not limited by what is wrong but by what is insignificant. There is also the false which is limited and circumscribed by what is true, the erroneous principle surrounded by a halo of truth." Wolfgang Pauli was once asked if he considered wrong a certain article of physics which was particularly badly conceived, and he replied that this adjective would be too kind: the article was not even wrong.

The way to certainty is not linear; indeed, it is often full of really dramatic turns of events. Sometimes a discovery forces one to recognize that the way that one has been taking for a long time is in fact impracticable. Even if with great expenditure of energy one has found a way through an intricate wood, it is then important to go back and start again. "Scientific progress is sometimes also made by taking some steps backwards. To assess one's own degree of ignorance correctly is sometimes a healthy and necessary step," observed Herbert Reeves. But it happens that, in particular, "negative" discoveries of this kind—the "counterexample" in mathematics—give the lie to and destabilize a large part of the scientific structure and end up having an extraordinary importance and weight. This is what De Giorgi calls "the exploitation of failure."

Ennio De Giorgi[11]

Returning to the image of mathematics as one of the many branches of the tree of Wisdom, we could say that whereas the theories already asserted, the theorems completely demonstrated, are the leaves, the flowers, the mature fruit, the problems still open, the conjectures still to be demonstrated (or refuted) are the buds, the flowers yet to open, the fruits which are still bitter, and the good health of the branch is attested by the abundance of both of these.

As for conjectures, I would note that generally the confirmation of the most interesting conjectures corresponds to a regular growth of science; the discovery of a counterexample which gives the lie to a very important conjecture represents a turning point that opens up broader and more fascinating horizons to science than earlier ones.

With a somewhat paradoxical phrase we could say that the normal growth of science follows the logic of the "exploitation of success," whereas the great turning points of science obey the logic of the "exploitation of failure." Of course with the paradoxical phrase "exploitation of failure," I do not want to trivialize the difficulties that accompany the great turning points of science or to record the joy and ignore the misunderstandings, the delusions, and the discomfort involved in many cases. It is enough to think, for example, of the profound discomfort with which many mathematicians and physicists accepted relativity and quantum mechanics, of the cost of the move from quiet work on the well-consolidated theories of classical mechanics to a new way guided by the hope of eventually finding a yet richer and broader harmony than that already found by Pythagoras, Archimedes, Galileo, Kepler and Newton. . . .

Turning to mathematics, the most famous counterexample of antiquity was the discovery of the incommensurability of the diagonal with the side of the square, i.e., the fact that their relationship cannot be expressed as a relationship between two whole numbers (in algebra the same result can be expressed by saying that the square root of 2 is an irrational number).

Certainty and Impossibility: When Theory Says "Stop!"

In the natural sciences, and in particular in physics, science gets close and sometimes touches on the intrinsic limit of what it can say. The problem of such an intrinsic boundary, a limit that the law within it in some way "declares" that it touches, was a possibility that Helmholtz had already anticipated in the eighteenth century.

Hermann von Helmholtz[12]

The ultimate aim of the theoretical natural sciences is therefore to discover the ultimate immutable causes of natural processes. That all the processes can be traced back to such causes and that, in consequence, all nature has to be completely intelligible, or that there exist transformations which detract from the law of a necessary causality, and fall into a sphere of spontaneity and freedom, need not be decided here; it is clear that in any case science, the aim of which is to understand nature, must move from the presupposition of its intelligibility, concluding and investigating in conformity with such a presupposition, to the point of possibly being constrained to recognize the limits by irrefutable facts. ✺

Gödel's theorem (1931) indicated a limit of this kind from a mathematical point of view: a limit to the propositions that can be demonstrated or refuted on the basis of a certain finite system of axioms. There are "undecidable" propositions that cannot be demonstrated to be either true or false. In mathematics there are therefore questions that we are certain that we cannot answer: not for lack of the astuteness of mathematicians or because they have not taken enough thought, but simply because it is impossible to answer them.

Ennio De Giorgi[13]

[Gödel's theorem] asserts the existence of arithmetical propositions that cannot be decided: without going into details, which would be necessary to understand the content precisely, I hope that I will not betray the meaning too much by saying that in substance the theorem asserts that, given a finite system of axioms satisfied by the structure of numbers, there are infinite propositions regarding such a structure that cannot be either demonstrated or refuted on the basis of the given system (propositions relative to such a system that cannot be decided on).

This theorem of Gödel's constitutes a counterexample in respect of the program of finite axiomatization of mathematics proposed by another of the greatest mathematicians of our century, David Hibert, which initially aroused distrust or disappointment among mathematicians. Today, reflecting on the meaning of this theorem, I would say that for every mathematician it can be a reason for joy and hope, bringing awareness that the riches implicit in the intuitive idea of a whole and inexhaustible number that future generations of mathematicians can always (without renouncing the many brilliant achievements of the past) then clarify later and deepen that intuition without which the structure of whole numbers (the first example of infinity encountered by mathematicians) is never trivialized. ✺

In an analogous way to what happens through Gödel's theorem in mathematics, in the natural sciences too, and especially in physics, the most advanced and most successful theories have managed to identify from within them boundaries beyond which, for their very coherence, they cannot go. The uncertainty principle in quantum physics, the cosmic variance in cosmology, are examples of limits intrinsic to the theories themselves, "self-imposed" barriers of the physical framework that with great precision explains a vast number of phenomena. Here a limit is reached that has nothing to do with the fact that some phenomena are not explained by the theory in a satisfactory way; it is a limit that derives from the fact that we can demonstrate that we cannot go beyond certain frontiers. Thus, in some cases science leads us to a new type of certainty: we can be certain of what we can never know.

John Barrow[14]

Bookshelves are stuffed with volumes that expound the successes of the mind and the silicon chip. We expect science to tell us what can be done and what is to be done. Governments look to scientists to improve the quality of life and safeguard us from earlier "improvements." Futurologists see no limit to human inquiry, while social scientists see no end to the raft of problems it spawns. The contemplation by our media of science's future path is dominated by our expectations of great interventions: cracking the human genetic code, curing all our bodily ills, manipulating the very atoms of the material universe, and, ultimately, fabricating an intelligence that exceeds our own. Human progress looks more and more like a race to manipulate the world around us on all scales, great and small.

It would be easy to write such a scientific success story. But we have another tale to tell: one that tells not of the known but of the unknown; of things impossible; of limits and barriers which cannot be crossed. Perhaps this sounds a little perverse. Surely there is little enough to say about the unknown without dragging in the unknowable? But the impossible is a powerful and persistent notion. Unnoticed, its influence upon our history has been deep and wide; its place in our picture of what the Universe is like at its deepest levels is undeniable. But its positive role has escaped the critics' attention. . . . Our goal is to uncover some of the limits of science: to see how our minds' awareness of the impossible gives us a new perspective on reality.

When we are young we think we know everything. But if we grow wiser as we grow older we will gradually discover that we know less than we thought. The poet W. H. Auden wrote of human development that "between the ages of twenty and forty we are engaged in the process of discovering who we are, which involves learning the difference between accidental limitations which it is our duty to outgrow and the necessary limitations of our nature beyond which we cannot trespass with impunity."

Our collective knowledge of the nuts and bolts of the Universe matures in a similar way. Some knowledge is simply the accumulation of more facts, broader theories, and better measurements by more powerful machines. Its rate of growth is always limited by costs and practicalities that we steadily overcome by attrition, little by little. But there is another form of knowledge. It is the awareness that there are limits to one's theories even when they are right. While the modest investigator might always suspect that there are things that will remain beyond our reach, this is not quite what we have in mind. There is a path of discovery that unveils limits that are an inevitable by-product of the knowing process. Discovering what they are is a vital part of understanding the Universe. This means that the investigation of the limits of our knowledge is more than a delineation of the boundaries of the territory that science can hope to discover. It becomes a crucial feature in our understanding of the nature of this collective activity of discovery that we call science: a paradoxical revelation that we can know what we cannot know. This is one of the most striking consequences of human consciousness.

There is an intriguing pattern to many areas of deep human inquiry.

Observations of the world are made; patterns are discerned and described by mathematical formulae. The formulae predict more and more of what is seen, and our confidence in their explanatory and predictive power grows. Over a long period of time the formulae begin to argue that they will allow us to understand everything. The end of some branch of human inquiry seems to be in sight. Books start to be written, prizes begin to be awarded, and of the giving of popular expositions there is no end. But then something unexpected happens. It's not that the formulae are contradicted by Nature. It's not that something is seen which takes the formulae by surprise. Something much more unusual happens. The formulae fall victim of a form of civil war: they predict that there are things which they cannot predict, observations which cannot be made, statements whose truth they can neither affirm nor deny. The theory proves to be limited, not merely in its sphere of applicability, but to be self-limiting. Without ever revealing an internal inconsistency, or failing to account for something we have seen in the world, the theory produces a "no-go" statement. . . . Only unrealistically simple scientific theories avoid this fate. Logical descriptions of complex worlds contain within themselves the seeds of their own limitation. A world that was simple enough to be fully known would be too simple to contain conscious observers who might know it. ✺

Certainty and Knowability: A Gift That We Neither Understand nor Deserve

No one knows what point our understanding of the reality of nature will reach in the future. With research human beings engage in a hand-to-hand struggle over the territory of nature into the unknown, but we do not know what the outcome of this struggle will be. No one can foresee whether that of science is a potentially unlimited ascent or a splendid but ephemeral adventure, a parenthesis destined to reach a climax and then stop, or even regress and disappear. But it is an extraordinary aspect of the "struggle with the unknown" that we can already recognize and assert today the very fact that this struggle is possible. The phenomenon of this capacity that we have to understand the reality of nature, to unveil at least some of its secrets, is indeed surprising.

We can investigate the nature of subatomic particles, the dimensions of which are fifteen orders of magnitude below the smallest dimensions that can be perceived by our senses, and we are in a position to describe their behavior with unheard-of precision, thanks to the discovery of laws of physics that move away in a radical manner from any relation of regularity that we can perceive with our direct experience. Thus, cosmologists can press on to describe processes that took place in the newly born universe, a very few instants—even tiny fractions of a second—after the beginning of cosmic history.

It is not easy to believe that there were selective advantages in favoring the emergence in human beings of this capacity at the time when early humans were struggling to survive in the depths of prehistory: the capacity to survive in the savannah would not seem to depend on the predisposition of the mind to solve differential equations. . . .

In any case, whatever may have been the way that has made it possible to sustain a relationship of such a deep awareness of the universe, the fact that such a relationship exists is something that is "not due," a circumstance that seems gratuitously to offer itself to us as an excess, as a "luxury" granted to human beings. It is something that we could probably do without for our survival, today as 2 million years ago. But without this capacity, human beings would be denied the giddiness of the awareness of the cosmic environment in which we are put, of the fabric and order of what constitutes reality.

Many of the greatest scientists have been profoundly struck by this circumstance and have expressed their rational amazement.

Albert Einstein[15]

The very fact that the totality of our sense experiences is such that by means of thinking (operations with concepts, and the creation and use of definite functional relations between them, and the coordination of sense experiences to these concepts) it can be put in order, this fact is one which leaves us in awe, but which we shall never understand. One may say "the eternal mystery of the world is its comprehensibility." It is one of the great realizations of Immanuel Kant that the setting of a real external world would be senseless without this comprehensibility.

In speaking here concerning "comprehensibility," the expression is used in its most modest sense. It implies: the production of some sort of order among sense impressions, this order being produced by the creation of general concepts, relations between these concepts, and by relations between the concepts and sense experience, these relations being determined in any possible manner. It is in this sense that the world of our sense experiences is comprehensible. The fact that it is comprehensible is a miracle. . . .

The aim of science is, on the one hand, a comprehension, as complete as possible, of the connection between the sense experiences in their totality, and, on the other hand, the accomplishment of this aim by the use of a minimum of primary concepts and relations. (Seeking, as far as possible, logical unity in the world picture, i.e., paucity in logical elements.)

. . . The essential thing is the aim to represent the multitude of concepts and theorems, close to experience, as theorems, logically deduced and belonging to a basis, as narrow as possible, of fundamental concepts and fundamental relations which themselves can be chosen freely (axioms). The liberty of choice, however, is of a special kind; it is not in any way similar to the liberty of a writer of fiction. Rather it is similar to that of a man engaged in solving a well-designed word puzzle. He may, it is true, propose any word as the solution; but, there is only one word which really solves the puzzle in all its forms. It is an outcome of faith that nature—as she is perceptible to our five senses—takes the character of such a well-formulated puzzle. The successes reaped up to now by science do, it is true, give a certain encouragement. ✺

What Einstein calls "the miracle" and "the eternal mystery" of the comprehensibility of the world is a fact to be recognized. In one of his most successful syntheses, he affirms that "the most incomprehensible thing about the universe is the fact that it is comprehensible." That the world presents itself with an order that we can appreciate, that the universe "lets itself be known" by human beings, remains one of the deepest mysteries. In particular, it is anything but a foregone conclusion that nature is so well described by a particular language, that of mathematics, which shows itself extraordinarily effective in the formulation of the laws of physics. Wigner powerfully expresses the perception of the exceptional nature of this correspondence and the gratuitousness with which it is encountered.

Eugene Paul Wigner[16]

Most more advanced mathematical concepts, such as complex numbers, algebras, linear operators, Borel sets—and this list could be continued almost indefinitely—were so devised that they are apt subjects on which the mathematician can demonstrate his ingenuity and sense of formal beauty. . . . The mathematician could formulate only a handful of interesting theorems without defining concepts beyond those contained in the axioms and . . . the concepts outside those contained in the axioms are defined with a view of permitting ingenious logical operations which appeal to our aesthetic sense both as operations and also in their results of great generality and simplicity. . . .

It is difficult to avoid the impression that a miracle confronts us here, quite comparable in its striking nature to the miracle that the human mind can string a thousand arguments together without getting itself into contradictions or to the two miracles of the existence of laws of nature and of the human mind's capacity to divine them. . . .

. . . The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research and that it will extend, for better or for worse, to our pleasure even though perhaps also to our bafflement, to wide branches of learning.

It is possible for reason to "follow" reality and to arrive at points of certainty even in territories in which the imagination breaks down. Mathematics is the guide that surprisingly keeps us on the tracks of the real world. And it is the greatest expression, in the scientific field, of the fact that our mind is called to adjust itself to reality, not vice versa.

Pascual Jordan[17]

We have seen in the case of the parallels that there is a logical possibility of constant relations between them; although, if we want to know what physical experience (and consequently theory) says about this we must jump to the higher level of the theory of relativity. Einstein was certain of the real physical significance of the logical possibilities that mathematicians have formulated, indeed for the first time he made these profound mathematical theories fruitful for physics.

His ideas can only be hinted at here. On the higher level of the theory of relativity they are concerned with the force of gravity and establish that it confers a very slight "curvature" on our space. Hence it is possible (here for the understanding of the physical world we should again resort to mathematics) to get a little closer to the laws of non-Euclidean geometry, imagining, for example, a sphere and considering its "maximum circumferences" (those obtained by cutting the sphere with a plane that passes through its center). Also with these circumferences, or with their arcs, we can construct "triangles," and when we measure the sum of the angles in these triangles it transpires that this is greater than two right angles. Otherwise these triangles traced on the sphere obey the same laws as triangles in Euclidean geometry; hence the spherical surface offers a concrete model of non-Euclidean surfaces within Euclidean space. A non-Euclidean space will then be something of this kind but in three rather than two dimensions: here intuition rebels, but both mathematics and logical analysis assert that this possibility exists. For a spherical triangle of determinate magnitude the difference of the sum of its angles from the value of two right angles is greater to the degree that the radius of the sphere is lesser, i.e., the more curved the surface of the sphere is. Thus, in general, mathematicians speak of the curvature of a non-Euclidean space to express its difference from a Euclidean space.

. . . We must not expect nature to adapt itself to what is more convenient for us and more customary to think; on the contrary *we* must seek to adapt our ideas to nature and reality. However difficult it is to free ourselves from the chains of our human limited vision of reality (as in the case of parallels or of relative velocities), the freedom that our thought has in such a mode is great. We *need* this freedom to be able to grasp the reciprocal connections and the marvelous laws of natural phenomena and to be able to imitate them mentally. If we have to admit on the one hand that our intuition is little help to our thought and is often deceived, we nevertheless recognize with all the greater certainty that our mind has the capacity to overcome the limits of our intuition.

Certainty and Person: Belief in the Reality of Atoms and Electrons

We have seen in what sense we may speak of positive certainties in the scientific sphere, but how do we arrive at such a goal? It does not seem that scientists arrive at a certainty of the type "The sun is a star" (or "The universe is evolving" or "The proton is made up of quarks") by following the rigid way of logic and demonstration. Usually one does not end up saying "Things are like this" by following a rigid procedure, as an algorithm of the inevitable outcome. Even in the field of science, certainty is a judgment on reality that involves the whole human subject, who is called to bring reason into play in a breadth that surpasses its capacity for logical deduction. Astronomers have obtained much specific quantitative knowledge about the sun by using what we normally call the scientific method, but they can be certain that the sun is a star by using reason according to a different method, more like that with which a detective can sometimes discover the culprit: through a convergence of indications.

Detectives can sometimes accumulate indications that allow them to arrive at final conclusions that do not require further investigations: "how things have gone" becomes definitively clear. The certainty that may arise out of scientific investigation is like this. In time, the observations and the experiments relating to a certain phenomenon can make it possible to accumulate a large quantity of evidence and experimental data. Each of these results is not conclusive in itself, but constitutes an indication, a sign that "points" toward a certain conclusion. The force of a new convergent indication will be all the greater the more this comes from an unexpected direction, independent of all the other clues. The certainty emerges and is consolidated in time; it requires living for a long time with open questions, maturing in reasonable judgment shared by other reasonable people. It can happen that all the indications and experimental facts no longer allow an escape: there is no longer room for doubt in a healthy mind that is capable of understanding the data.

But if this is the case, it is important to recognize that in scientific knowledge too, as in every kind of knowledge, freedom and responsibility are in play—and therefore the human person—to the risk of judgment, to the point of saying, "I believe that things are like this."

Michael Polanyi[18]

Any account of science which does not explicitly describe it as something we believe in is essentially incomplete and a false pretense. It amounts to a claim that science is essentially different from and superior to all human beliefs that are not scientific statements—and this is untrue.

To show the falsity of this pretension, it should suffice to recall that originality is the mainspring of scientific discovery. Originality in science is the gift of a lonely belief in a line of experiments or of speculations which at the time no one else considered to be profitable. Good scientists spend all their time betting their lives, bit by bit, on one personal belief after another. . . .

Science or scholarship can never be more than an affirmation of the things we believe in. These beliefs will, by their very nature, be of a normative character—that is to say, claiming universal validity—and they must also be responsible beliefs, held in due consideration of evidence and of the fallibility of all beliefs;

but eventually they are ultimate commitments, issued under our personal judgment. To all further critical scruples we must at some point finally reply: For I believe so.

There is no scientist who investigates reality without the positive hypothesis of the existence of a meaning, without following the hope of a mysterious yet real order in the universe; looking at the fragments of his data he seeks a perspective that can make sense of all that he sees without excluding anything, certain that such a perspective somewhere exists. Every act of a researcher "in action" is based completely on his trust in the possibility of an authentic, albeit partial, understanding of the world. Commenting on the passage from Polanyi quoted above, Thomas Torrance has observed that "the great scientists take account of the fact that there is an elementary faith, intuitive and unshakeable, in the significant nature of the things of the universe, faith in the intelligibility of the universe, faith in its pervasive and unitary character, faith in its regularity and stability and constancy and simplicity, which stands behind all scientific activity and permeates it, extending from one end of their investigations to the other; and it is also faith in the possibility of grasping the real world with our concepts, together with the faith that the intelligibility of the real world also applies when it transcends our conceptions and formulations; it is faith in truth over which we have no control, but in the service of which our human reason fails or prevails. Thus faith in reason itself and faith in the intelligible structure of the universe of which we cannot give any logical demonstration are bound up inseparably according to the obligatory way that reality itself imposes on our minds."[19]

This "elementary faith," as also emerges from the following passage from Max Planck, is that primordial level of conscience without which there is no hope of any knowledge.

Max Planck[20]

An intuition of the world can never be demonstrated scientifically, but it is certain that it resists any tempest as long as it remains in accord with itself and the facts of experience. It cannot be said that even in the most precise of all the sciences it is possible to proceed without an intuition of the world, or without hypotheses that cannot be demonstrated.

In physics, too, one is not blessed without faith, or at least without faith in a reality outside us. It is this certain faith that indicates the way to the creative driving impulse which offers the occasions necessary for the imagination that sees how the land lies, which alone can recognize the spirit wearied by failures and spur it to new leaps forward. A scientist who does not allow himself to be guided by a hypothesis in his labors, however prudent and provisional, *a priori* renounces any deep understanding of his own results.

Those who reject belief in the reality of atoms and electrons, or in the electromagnetic nature of light, or in the identity of the heat of bodies and movement, will certainly succeed in never getting involved in logical or empirical contradictions. But it remains to be seen how they will succeed, starting from their perspective, in advancing scientific knowledge.

Granted, faith in itself does not succeed, and as the history of all science shows, it can also lead to error and degenerate into narrow-mindedness and fanaticism. For faith always to be a trusted guide, it has continually to be controlled on the basis of the laws of thought and experience, and nothing contributes toward this aim more than conscientious, laborious, and detailed work by the individual researcher. Even a king of science must, if the case arises, be able to know how to and to want to engage in hard graft in the laboratory or the archive, in the open air or at the desk. And it is in these hard struggles that the intuitions of the world mature and become refined. Only the one who has personal experience of this process will fully appreciate its significance. . . .

. . . Faith is the force that gives effectiveness to scientific material brought together, but it can go one more step forward and affirm that in collecting the material, too, a prior and present faith can do good service in more profound nexuses. It points the way and sharpens the senses.

This "elementary faith" is the indispensable basis for the rise of all science and of other forms of knowledge acquired. Torrance also underlines "the irrational opposition of intuitive certainty (faith) and reason. The former is a mode of rationality on which the latter is based, to remain faithful to what it seeks to understand; therefore intuitive certainty constitutes the most fundamental form of knowledge on the basis of which the whole of the subsequent rational investigation proceeds."[21]

The one who says "I believe that things are like this" is a human being. It is a fact that science is a human undertaking, and corresponds to a mode of observing and knowing reality. It is not possible to eliminate the human subject from the process of knowledge: even scientific knowledge only can be "personal knowledge."

John Polkinghorne[22]

We have, in the course of the pursuit of truth, to be willing always to respect the nature of the object of our inquiry. Some may feel disappointment that scientific method cannot be given a crisper, more cut-and dried, characterization, but I am persuaded that the chiaroscuro of the personal knowledge account is entirely in accord with the actual character of scientific activity. The view I am defending is called critical realism. "Realism," because it claims that science actually does tell us about the physical world, even if it does not do so finally and exhaustively. "Critical," because it recognizes the subtlety and ultimate unspecifiability of the scientific method.

If what I claim is true, two things follow. One is that science is not radically different from other forms of human rational inquiry. It too requires the act of intellectual daring, of commitment to a potentially corrigible point of view. It too involves reliable but unspecifiable acts of judgement. Science's superior power to settle questions lies, not in its invincible certainty, but in the openness to testing that results from its concern with aspects of reality sufficiently impersonal in their character to be open to repetitive investigation and consequent experimental checking.

The other consequence I wish to draw from the recognition of science as a personal knowledge is that science's verisimilitudinous success encourages us to believe that rational, if precarious and unquantifiable, strategies of investigation of this kind are capable of leading us to an enhanced understanding of reality. One could not have deduced beforehand that this would be so (logicians such as Popper demand too much in that respect), but it is a contingent but fortunate fact about the world that we can learn much of its nature in this way.

Certainty and Sign: That Italian Night, with No Moon and Full of Stars

The limits of what we can know through science are inherent in the method itself, or in the type of questions that it sets out to answer. In this famous passage Galileo affirms the distinction and the limits of the newborn scientific method: the scientist goes in search of the "affections," not the ultimate essence of things.

Galileo Galilei[23]

Either we want by speculation to attempt to penetrate the true and intrinsic essence of natural substances or we are content with noting some of their affections. Attempting to reach the essence is no less impossible and the labor no less vain in the nearest elementary substances than in the most remote and celestial substances, and I seem to to be equally ignorant of the substance of the earth as of the moon, the elementary clouds as of the sun spots, nor do I see that in investigating these nearby substances we have another advantage than an image of particulars, all equally unknown, by which we steer our course, passing with very little or no achievement from one to the other. And if, when investigating the substance of the clouds, I am told that it is a humid vapor, I again want to know what the vapor is; I will perhaps be told that it is water, by virtue of the reduced heat, and resolved into that; but I, equally doubtful what water is, by continued research will finally understand it to be that body of fluid which runs through the rivers and which we continually use and deal with; yet such knowledge of water is only nearer and dependent on more senses, but not more intrinsic than that which we have of the clouds. And in the same way I no longer understand the true essence of the earth or of fire, that of the moon or the sun; and this is that knowledge which is reserved for those in the state of bliss, and not before. But if one prefers to stop here in the apprehension of some affections, it does not seem to me that we should despair at being able to follow even the bodies most distant from us, any more than those closest; indeed we may be able to do so more exactly in the case of the former than in that of the latter. And who does not understand better the periods and the movements of the planets than those of the waters of various seas? Who does not know that the spherical shape of the lunar body was understood much earlier and more specifically than that of the earth? And is there not still controversy as to whether the same earth stays immobile or moves around, while we are very certain of the movements of quite a few stars? I want to infer that if we attempt to investigate the substance of the solar spots, only some of their affections, like the place, the movement, the shape, the size, the mutability, the production and the dissolution, cannot be understood by us, and we are then put in a better position to philosophize about other more controversial conditions of natural substances; by raising them we are finally at the ultimate goal of our labors, that is, the love of the divine Architect, and keep the hope of being able to learn in Him, the source of light and truth, any other truth. ✺

To those who seek the truth, science can only offer partial truths, relating to a limited segment of the real. The possibility of knowing something of the features of the universe, of being able to unveil some of its laws, rather than being satisfying, increases the thirst for an ultimate meaning that moves and gives consistency to everything.

But if it is true that science does not speak of the ultimate nature of things, it indirectly implies it and makes it easier to perceive it. Scientific knowledge does not relate to the whole truth of the object but provides the conditions for contemplating the beauty of things at close quarters; it brings out the order, the harmony, and also the unpredictability of the universe, makes it almost inevitable that a sincere person will have a solid perception of the presence of the vast mystery on which all rests. Natural reality, the starry sky that is always there and under the eyes of all, and which science makes known in greater depth, is a sign of that mystery. But it is simplicity, more than scholarship or brilliance, that is the source of the knowledge indispensable for recognizing it.

Enrico Fermi[24]

Many years have passed, but I remember it as if it were yesterday. I was very young and had the illusion that human intelligence could arrive at anything. That was why I was utterly caught up in my studies. It was not enough for me to read many books; I meditated deep into the night on the most abstruse questions. Severe neurasthenia obliged me to stop and leave the city, full of temptations for my exhausted brain, to take refuge in the remote Umbrian countryside. I was reduced to an almost vegetative, but not animal, life. I read a little, I prayed, I spent a lot of time in the flowery countryside (it was May), I contemplated the dense masses and green streaks of the peppers, the lines of poppies that extended along the canals, the blue mountains that shut off the horizon, the tranquil human work in the fields and the cottages. One evening, indeed one night, while I was waiting for sleep to come, sitting on the grass in a field, I heard the relaxed conversation of some country people near by; what they were saying was very simple, but neither vulgar nor frivolous, as is usual among other classes. Our countryfolk speak rarely, and when they do it is to say something appropriate, sensible and sometimes wise. Finally they fell silent, as if the serene and solemn majesty of that Italian night, with no moon and full of stars, had cast some mysterious spell on their simple spirits. The silence, but not the spell, was broken by the serious voice of a large countryman, coarse in appearance, who was lying on the grass with his eyes directed to the stars and exclaimed, "How beautiful it is! And yet there are those who say that God does not exist." I repeat, this phrase of the old countryman in that place at that time, after months of arid study, so touched my mind that I remember the scene as if it were yesterday. A great Hebrew prophet remarked three thousand years ago, "The heavens declare the glory of God." One of the most famous philosophers of modern times wrote, "Two things fill my heart with admiration and reverence, the starry sky above me and the moral law in my heart." That Umbrian countryman did not even know how to read. But in him, guarded by a simple and laborious life, there was a small corner in which the light of the Mystery descended with a power not so inferior to that of the prophets and perhaps superior to that of the philosophers. ✺

Sign 6

He shewed me a little thing, the quantity of an hazel-nut,
in the palm of my hand; and it was as round as a ball.
I looked thereupon with eye of my understanding, and thought,
'What may this be?' And it was answered thus:
"It is all that is made." **JULIAN OF NORWICH**

They were unable from the good things that are seen
to know the one who exists,
nor did they recognize the artisan while paying heed to his works;
but they supposed that either fire or wind or swift air,
or the circle of the stars, or turbulent water,
or the luminaries of heaven
were the gods that rule the world.
If through delight in the beauty of these things
people assumed them to be gods,
let them know how much better than these is their Lord,
for the author of beauty created them.
And if people were amazed at their power and working,
let them perceive from them how much more powerful
is the one who formed them.
For from the greatness and beauty of created things
comes a corresponding perception of their Creator.

WISDOM 13:1–5

Imagine a naturalist who one morning, early as always, enters his botanical laboratory. On opening the door, unexpectedly he notices some dark blue flowers on his desk. For a moment he is perplexed. Where do they come from? The young naturalist turns toward the table and bends over the bunch of flowers, captured by his curiosity as a specialist, and tries to recognize the species. Immediately he understands that they come from the violet family but of course that is not enough; he wants to understand precisely what they are. He begins to look attentively at the corolla and observes the rosette at the base that has no stolons. He is disconcerted and seems anxious to understand more. Then he takes a flower from the bunch. He sniffs it and notes the absence of perfume; then he observes with a magnifying glass the leaves on the small stem that seem linked together, with lance-shaped stipulas. He notes other details that only his expert eye can discern and appreciate. He has come to the conclusion that this is an example of the *viola hirta*, a plant of simple and extraordinary beauty. In the silence of the empty laboratory, the young man sits at the table. For a moment he turns and looks at the flowers again. Suddenly the telephone rings and, as every morning, he begins his intensive day's work.

But that day, behind all the motions he was going through, from the first minute to the last, a question kept nagging him: "What is the meaning of these flowers?" "Is there (or is there not) a meaning behind their presence here on the table?" or "Who put them on my table?" The question was all the more insistent as he had a premonition: for some time he had in fact noticed that his attractive assistant seemed to show a particular interest in him. So this bunch of flowers was "a sign of something else," or at least it could be. It was the sign of a presence that would enhance and fulfill in an incomparable way the natural beauty of the flower that he had observed that day and enjoyed with an unusual intensity. Of course, there could be different and less satisfactory explanations for the provenance of the flowers. Had they been put there the previous evening by someone from the laboratory who intended to analyze them the next day? Or even, to promote the new activity of the research center, had they decided to put a bunch of flowers on "all" the tables in the laboratory? But probably our friend already knew that this was not the case.

The whole universe, the natural world and its phenomena, have some similarity to such a bunch of flowers left there on the table for each one of us. The very face of reality changes radically if it is recognized as the sign of a good and the expression of a meaning, at least as a possibility, or if it is experienced in its brutal and sordid existence without hope of meaning and friendship with it. Reality presents itself freely, with a harmony, a fertility that seem to go beyond what we would "reasonably" expect; it calls for an explanation, an explanation that certainly will not come from within the capacity of scientific investigation, but the need of which the results of modern science seem to amplify.

Scientific experience is sustained by the human desire to become aware of the world in which we are immersed, to be able to enjoy its beauty and also to some degree to use it to our own advantage. But at the very moment in which such knowledge is gained, the scientist is confronted with an inevitable question: is there or is there not a meaning in that reality which he observes and in part understands? Are the beauty, the order, the contingency, the variety of the world that through science we appreciate in the individual phenomenon as in the globality of the cosmos "significant facts," or are they not? Are they, or are they not, signs of a more profound reality, going beyond the phenomenon itself? The physical world, which emerges to observation with its abundant riches, seems almost to invite freedom and to solicit reason to consider a deeper level of reality of which the "measurable" datum is, as it were, the surface, a level of the real to the threshold of which science takes us, but which goes beyond the horizon of what it is capable of coping with.

From this perspective, science today opens up horizons that were unthinkable a century ago. For example, various pieces of evidence in current cosmology show how the universe has been subject to changes—is the protagonist of a history, a history that, traced backward, leads to the threshold of a cosmic infancy, an original phase from which the natural world in its inexhaustible variety began. Who knows what other discoveries and dramatic turns cosmology will produce in the coming years? At any rate, if the great interpretative lines of what has happened are correct, we are confronted with a notable fact: the complex tissue of natural reality that we observe today comes from an extraordinarily simple primordial state that is at the same time incredibly specific. It is a primordial simplicity capable of containing the seed of the diversity and complexity that are beneath our eyes. We notice then that not only in the initial instants but at every moment of cosmic history the fundamental properties of nature are involved in a very subtle game, the result of which is the possibility—not the necessity—of the appearance at some point of the universe—certainly here on the earth—of complex systems leading up to life. And on the other hand, this dramatic situation does not seem to be written rigidly into the initial conditions, even if these last (the initial conditions) present themselves as strictly indispensable; rather, the course of the complexity here on our planet needed fortuitous and unpredictable events. Indeed, for many scientists it is natural to think of a profound unity of the cosmos, of a disposal of events that seem to be the features of a design in which our presence appears anything but secondary.

The question, or the presentiment, arises that the natural world might be a sign of "something beyond itself." This is a rational question just as it is fully rational to ask the question: "Did perhaps someone put this bunch of flowers on my table?"

From the testimonies of many scientists, it is possible to document the emergence of the question of whether, when it is known from a scientific perspective, nature indicates a reality beyond itself. Obviously many different attitudes can be found both in the past and the present. There are those who from the beginning avoid the problem and consider that questions of this type are senseless; normally this is the position of someone who denies *a priori* credibility to what does not fall within the scope of the "scientific method"; these same questions are thought meaningless in that they cannot be treated scientifically. However, many great scientists in different ways have accepted and still accept the basic relevance of the question in a great variety of modes and expressions, with a dramatic perception of the risk that our interpretations involve. There are those who reply in the negative, excluding the possibility that natural reality can contain any value as a "sign"; it is said to have no meaning beyond itself. And there are those who argue that the physical world suggests itself in an irresistible way as a sign of something other, something that natural phenomena indicate but do not exhaust.

Let's return for a moment to our young botanist. The force of the hypothesis that that bunch of flowers had a certain meaning, that it could be a "sign" of a greater presence, was bound up with a previous experience: the perception of attention from his young assistant. If he had found the flowers on the table, but had not had that experience, the questions "Who put these flowers on the table?" and "What significance do they have?" would probably have emerged in him with the same inevitability. But the way to the answer would have seemed very confused and difficult. Thus, for the scientist who seeks to judge the question on the basis of the resources of scientific knowledge alone, the situation is almost desperate: this was felt by Cardinal Henry Newman when he asserted: "I believe in a design because I believe in God, not in a god because I see the design."

Sign and Knowledge: How Should We Look at Sculptures? From a Distance or Close Up?

Science to some degree corresponds to a need to know present in every human being. However, it is important to have a clear awareness, against any absolutist claim, that the scientific explanation is partial, in the sense that it picks up a very select part of reality and of the experience that we have of it.

Victor F. Weisskopf[1]

Let me come back to the question, Is physics human? I definitely would answer this question in the positive. It is human because it is nothing but a highly developed form of the urge to find out where we are in the environment into which we were born. This urge is common to all people, which explains why it is an activity in which human beings from all countries and cultures can and do participate equally.

. . . I believe that some of the aversions to physics and to science in general are connected with the rapid growth of science. It has led to the generally accepted claim that, in principle, science can and will find an explanation for every human experience.

I am not so sure that this claim is justified—but even if it were, the scientific explanation of a human experience does not necessarily touch all aspects of this experience. Indeed, in some cases it may not include the most relevant aspects. A simple example is the phenomenon of an artistic experience, say the enjoyment of a Beethoven sonata. It can be interpreted acoustically or neurophysiologically or even psychologically. However, there is something in that experience that is not covered by these scientific descriptions; yet that something is probably the most relevant part of it.

There are many other examples in the relations between human beings and between man and nature in which scientific interpretation may not cover all the aspects of human experience. This is particularly so for those aspects that are connected with concepts such as love, dignity, and ethics. Perhaps the recognition of the intrinsic value of physics could be enhanced if there were a greater awareness of the fact that science is only one way—albeit a very important one—of establishing a relation between mankind and its natural and social environment. ✺

There is always something that extends beyond scientific explanations. In particular, beauty, on which we have already dwelt, brings about questions and points beyond the object itself (whether this is a natural phenomenon, a physical law, or a mathematical theorem).

At least in some cases we can recognize symmetries and preferential relations, which can be specified quantitatively, and which correspond to our perception of beauty; however, the emergence of beauty cannot be reduced to the interpretations that scientific analysis succeeds in providing.

Henry Margenau[2]

"Why is there so much beauty in nature?" We do not believe that beauty is only in the eye of the beholder. There are objective features underlying at least some experiences of beauty, such as the frequency ratios of the notes of a major chord, symmetry of geometric forms, or the aesthetic appeal of juxtaposed complementary colors. None of these has survival value, but all are prevalent in nature in a measure hardly compatible with chance. We marvel at the song of the birds, the color scheme of flowers (do insects have a sense of aesthetics?), of birds' feathers, and at the incomparable beauty of a fallen maple leaf, its deep red coloring, its blue veins, and its golden edges. Are these qualities useful for survival when the leaf is about to decay? ✺

Reality investigated scientifically is not a banal system enclosed in itself; on the contrary, it reveals complexity at every stage. The beauty that characterizes the great scientific syntheses appears multiform, capable of showing itself simultaneously at different levels.

Subrahmanyan Chandrasekhar[3]

When Henry Moore visited the University of Chicago some ten years ago, I had the occasion to ask him how one should view sculptures: from afar or from nearby. Moore's response was that the greatest sculptures can be viewed—indeed, should be viewed—from all distances since new aspects of beauty will be revealed in every scale. Moore cited the sculptures of Michelangelo as examples. In the same way, the general theory of relativity reveals strangeness in the proportion at any level in which one may explore its consequences. One illustration must suffice.

If one enlarges Einstein's equations to the Einstein–Maxwell equations, that is, the field equations appropriate for space pervaded by an electromagnetic field, and seeks spherically symmetric solutions, one obtains a solution describing a black hole with a mass and an electric charge. This solution was discovered by Reissner and by Nordström as a generalization of the well known solution of Schwarzschild. Because of the charge of the black hole, it is clear that if an electromagnetic wave is incident on the black hole, a certain fraction of the incident electromagnetic energy will be reflected back in the form of gravitational waves. Conversely, if a gravitational wave is incident on the black hole, a certain fraction of the incident gravitational energy will be reflected back in the form of electromagnetic waves. The remarkable fact is that the two fractions are identically the same, that is, for all frequencies. This result was not expected; the underlying cause for it has now been traced to the time-reversibility of the (classical) law of physics. This example illustrates how strangeness in the proportion is revealed by the general theory of relativity at all levels of exploration. And it is this fact, more than any other, that contributes to the unparalleled beauty of the general theory of relativity. ✺

There are different levels of complexity, and each relates to the next. Even within science, a single type of approach cannot reasonably claim to exhaust the whole hierarchy of knowledge. Human research can try, to use an expression of John Paul II from a speech in Cologne on November 15, 1980, to "grasp the complex unity of the truth solely in the diversity," that is, within a fabric of open and complementary knowledge. Richard Feynman, a genius of physics, arrived at a similar conclusion, starting from different presuppositions and a different view of the world.

Richard Feynman[4]

We have a way of discussing the world, when we talk of it at various hierarchies, or levels. Now I do not mean to be very precise, dividing the world into definite levels, but I will indicate, by describing a set of ideas, what I mean by hierarchies of ideas.

For example, at one end we have the fundamental laws of physics. Then we invent other terms for concepts which are approximate, which have, we believe, their ultimate explanation in terms of fundamental laws. For instance, "heat." Heat is supposed to be jiggling, and the word for a hot thing is just the word for a mass of atoms which are jiggling. But for a while, if we are talking about heat, we sometimes forget about the atoms jiggling—just as when we talk about the glacier we do not always think of the hexagonal ice and the snowflakes which originally fell. Another example of the same thing is a salt crystal. Looked at fundamentally it is a lot of protons, neutrons, and electrons; but we have this concept "salt crystal," which carries a whole pattern already of fundamental interactions. An idea like pressure is the same.

Now if we go higher up from this, in another level we have properties of substances—like "refractive index," how light is bent when it goes through something; or "surface tension," the fact that water tends to pull itself together, both of which are described by numbers. I remind you that we have to go through several laws down to find out that it is the pull of the atoms, and so on. But we still say "surface tension," and do not always worry, when discussing surface tension, about the inner workings.

On, up in the hierarchy. With the water we have waves, and we have a thing like a storm, the word "storm" which represents an enormous mass of phenomena, or a "sun spot," or "star," which is an accumulation of things. And it is not worth while always to think of it way back. In fact we cannot, because the higher up we go the more steps we have in between, each one of which is a little weak. We have not thought them all through yet.

As we go up in this hierarchy of complexity, we get to things like muscle, twitch, or nerve impulse, which is an enormously complicated thing in the physical world, involving an organization of matter in a very elaborate complexity. Then come things like "frog."

And then we go on, and we come to words and concepts like "man," and "history," or "political expediency," and so forth, a series of concepts which we use to understand things at an ever higher level.

And going on, we come to things like evil, and beauty, and hope. . . .

Which end is near to God; if I may use a religious metaphor. Beauty and hope, or the fundamental laws? I think that the right way, of course, is to say that what we have to look at is the whole structural interconnection of the thing; and that all the sciences, and not just the sciences but all the efforts of intellectual kinds, are an endeavor to see the connections of the hierarchies, to connect beauty to history, to connect history to man's psychology, man's psychology to the working of the brain, the brain to the neural impulse, the neural impulse to the chemistry, and so forth, up and down, both ways. And today we cannot, and it is no use making believe that we can, draw carefully a line all the way from one end of this thing to the other, because we have only just begun to see that there is this relative hierarchy.

And I do not think either end is nearer to God. To stand at either end, and to walk off that end of the pier only, hoping that out in that direction is the complete understanding, is a mistake. And to stand with evil and beauty and hope, or to stand with the fundamental laws, hoping that way to get a deep understanding of the whole world, with that aspect alone, is a mistake. It is not sensible for the ones who specialize at one end, and the ones who specialize at the other end, to have such disregard for each other. (They don't actually, but people say they do.) The great mass of workers in between, connecting one step to another, are improving all the time our understanding of the world, both from working at the ends and working in the middle, and in that way we are gradually understanding this tremendous world of interconnecting hierarchies.

On the surface of the descriptions offered by science, symbols are used to grasp the structure of phenomena and the formalism that describes it, typically mathematical symbols. These symbols are "signs" that relate to an underlying reality: this is the first level of the sign, the most elementary. But physical reality, too, represented by the formalism of the theory, is also in its turn like the surface of a deeper layer. To stop here would mean to be content with the surface of the phenomenon, with the object or the living being that one observes. The same phenomenon can in fact be observed from different perspectives: one can study the behavior of a swallow toward its young, one can investigate the very refined systems that it uses to fly, the chemical reactions that direct its metabolism, the individual cells that constitute it. And there is an even broader and more ambitious position that points beyond even the sum of all the different levels that can immediately be perceived and quantified. As Pavel Florensky asserts, research is open to the prospective character of reality. The stratum of the real accessible to empirical investigation is like the skin of a fruit that contains other surfaces, other strata, that cannot be reduced to one another, but are bound together by precise correspondences.

B – Imagine having a piece of glass and a piece of ice, polished in the same way. To all appearances these pieces—supposing that the ice is pure—are almost indistinguishable and it can seem that the piece of ice is not more interesting, or more beautiful, than the piece of glass. But in molecular structure the ice is superior to the glass, just as the sound of an orchestra is superior to that of a bazaar. There is music in the ice, but noise in the glass; in the ice there is harmony and order, in the glass chaos and disorder; in the ice there is organization, in the glass anarchy. Every particle of glass is alone by itself and at most collides with the one next to it: it is not a whole. With ice it is quite the opposite: here every particle occupies the place that belongs to it in the symmetrical texture of the whole, in the organization of the amazing determined structure. But this difference of internal structure, which is like a symbol of the difference between the psychological and the spiritual man, is at first sight perfectly imperceptible.

A – Would you like to move from these examples to a general discussion of method?

B – Yes. All science circumscribes the field of its researches, creating the schemes of its objects and in this way using a given collection of signs: it is these last which determine the object of the science as such. . . . Thus, for example, those two pieces of ice and glass of which I have spoken are absolutely indistinguishable on the basis of geometric research, in that this cannot enter into an examination of the internal *structure* of the body. If we then continued, our mechanical perspective would be exhausted and we would have the possibility of studying only the mechanical characteristics that determine a certain object: then we would be in a position to define the form of the body, the means, the element of inertia[6] and so on, but the *temperature* of the body, its electrical charge, its psychological phenomena, etc., would remain completely imperceptible to us as such. We are well aware that two bodies with equal mechanical characteristics but with different temperatures are very different, yet we are not in a position to grasp this difference by means of the methods of mechanics. If we then set out to observe these bodies from the point of view of physics, and to examine them according to those methods and means that physics uses for its study of objects, then we would deduce and grasp the difference between the two bodies and their precise difference in respect of temperature.

In the same way, the methods of physics do not allow us to distinguish animate from inanimate matter. If we also recognize that compared with inanimate matter, in animate matter particular chemical and physical processes happen, we cannot then even distinguish between the animate and the inanimate, in that it is always possible mentally to construct such a system of mechanisms to *postulate* a kind of conformation of the animate body by which from the perspective of physics it can be examined, first, in this relationship, as inanimate. Only *new* methods, which are not part of physics, allow us to discover the difference between animate and inanimate. The examples given refer to cases in which two objects which are indistinguishable in sense experience at a certain level become different in experience at another level.

A – . . . For greater clarity, would you please spell out once again briefly the two conceptions of the world, yours and mine? But try to be brief.

B – It's simple: the first is *empirical*, the second is *empiricism*. The *conception* that you have expounded can be called *naturalistic*, also in the sense that this term assumes within the known literary school, in that it contents itself only with the surface of reality, with *protocols* of this world, and wants to reduce a whole series of different things to these. Our conception of the world, through its substance, is different. We are not content with the *surface* of reality, we look for the *recognition* of its prospective character, we see "the cold heights, the evasive breadths." This prospective profundity consists in the fact that we do not level down the whole multiformity of reality to its surface only, to what we can perceive with the senses; we do not record reality, flattening it and dessicating it in the great account book of positivism. Behind the apparent stratum of the empirical there are other surfaces, other strata, which cannot be reduced to one another but are bound together by *correspondences*, and these correspondences are not conventional or connected to reality; they are determined by the very act that produces reality in the form of what is represented.

Potentially it is possible that the same identical initial data are provided for both you and us: the elements. But you—if you perceive more the reality which surrounds us *in this way* as affirmed, and do not think it simply *necessary* to perceive in this way—you construct with these elements a flat world, while we construct one of profound dimensions.

. . . To these initial data which are identical for you and for us, simply apply a species of actions *which structure* reality and you will arrive at a uniform reality. This is empiricism. If we now apply to the same data a *series* of acts, we will obtain a reality *articulated* in a multiform way. From a certain material you have constructed the object α and after that nothing remains; however, it proves that the materials of this object allow and demand *yet another* elaboration by means of new methods of construction. It is in this manner that the objects α, β, γ . . . etc., are constructed. However, these objects are not totally isolated from one another; being independent through their substance, they are in any case connected, through awareness, through the unity of the material of which they are constructed and in reality, through the fact that this material is given by our relationship with a single thing, these objects α, β, γ . . . are also individual aspects of a *single* thing, the different sides of its idea, of the substance. The objects α, β, γ . . . are for awareness, the parts, the sides of the thing. However, they are not equal. The object β, as a further elaboration of the same material which makes up part of α, includes in itself α, in a certain sense, but by itself it reveals itself to be in some way richer in content than α, so that it is something that also surpasses α. β, in relation to α, has the same function as a page of Goethe, depending on whether the person who examines it understands the poem or is illiterate. For the former there is something aesthetic beyond the visible letters put "black on white," whereas for the latter there is only "black on white."

In this way, as a consequence of the fact that different activities of the intellect apply in the construction of reality, our objects include in themselves all that yours include, but they also have many other things: among these "other things" the most important, the most essential, is the sense of what you have seen but have not read. Therefore the objects of the religious conception of the world are more symphonic, richer than those of the positivist view. It is legitimate to compare them with chords, if we call the objects of the positivists monotone.

But when all this is elaborated by the intellect, the same apparent stratum, that world of the senses which is constructed by means of the *positivist* action of the intellect, takes on a special importance, a particular meaning for us. This world submits, so to speak, to other higher worlds, becomes their representative and in a certain sense their vehicle: rejecting self-affirmation, its existence for itself, it becomes life *for another world*. With itself, such a world of the senses, "having lost its life," having become the instrument of another world with its body, bears it *within itself*, incarnates the other world in itself or transfigures it, spiritualizes it, and transforms itself with it into a *symbol*, that is, an organically live unity with what it represents of what it symbolizes and what is symbolized. The empirical world becomes transparent, and through the transparency of this world the ardor and radiant splendor of the other worlds become evident.

. . . Hence if you have called your view of the superficial world *naturalistic*, in the sense of the well-known literary school, it would be right to call ours *symbolic*, in that in it the knowledge of the world is at the same time a "contact with another world.". . . Every stratum is intrinsically significant and refers to another which is even more significant. ✺

At first sight, the behavior of simple systems appears to be described completely in terms of the individual components of which they are made up. But if we consider increasingly more complex systems, things change. The elementary particles that make up our body are identical to all the other. The electrons and the protons of which in the end the cells of my spinal medulla are made up are identical with the electrons and the protons that make up this table or the air that I breathe or the rocks on the moon. But who could argue that our being can be reduced to such a collection of particles? The variety of the "interconnected hierarchy" of which Feynman spoke, or Florensky's "prospective" reality, coincide with the overcoming of the reductionist position, an overcoming now supported by a growing number of scientists, first of all biologists. To the point that some have reconsidereda concept so far thought to be anathema by science, the concept of "final causality."

William Homan Thorpe[7]

The behaviour of large and complex aggregates of elementary particles, so it turns out, is not to be understood as a simple extrapolation of the properties of a few particles. Rather, at each level of complexity entirely new properties appear, and the understanding of these new pieces of behaviour requires research which is as fundamental as, or perhaps even more fundamental than, anything undertaken by the elementary particle physicists. ✺

Robert Rosen[8]

Complex systems can allow a meaningful, scientifically sound category of final causation; something which is absolutely forbidden within the class of simple systems. In particular, complex systems may contain sub-systems which act as predictive models of themselves and/or their environments, whose predictions regarding future behaviors can be utilized for modulation of present change of state. Systems of this type act in a truly anticipatory fashion, and possess many novel properties. . . . ✺

Even in the sphere of physics, "reductionist" science par excellence, recent researches into chaotic systems have decisively enlivened the situation. Writing on chaos in an issue of *Scientific American*, a group of physicists have emphasized:

"Chaos brings a new challenge to the reductionist view that a system can be understood by breaking it down and studying each piece. This view has been prevalent in science in part because there are so many systems for which the behavior of the whole is indeed the sum of its parts. Chaos demonstrates, however, that a system can have a complicated behavior that emerges as a consequence of simple, nonlinear interaction of only a few components. The problem is becoming acute in a wide range of scientific disciplines, from describing microscopic physics to modeling macroscopic behavior of biological organisms. . . . The ability to obtain detailed knowledge of a system's structure has undergone a tremendous advance in recent years, but the ability to integrate this knowledge has been stymied by the lack of a proper conceptual framework within which to describe qualitative behavior. For example, even with a complete map of the nervous system of a simple organism, . . . the organism's behavior cannot be deduced. Similarly, the hope that physics could be complete with an increasingly detailed understanding of fundamental physical forces and constituents is unfounded. The interaction of components on one scale can lead to complex global behavior on a larger scale that in general cannot be deduced from knowledge of the individual components."[9]

And at a higher level we are faced with evidence that the level of awareness, the human level in which nature becomes aware of itself,[10] cannot be reduced to physics or to chemistry, and certainly not to biology. As Michael Polanyi points out: "There are irreducible proofs of existence in addition to those of morphological mechanisms, in the sensitivity that we ourselves experience and that we observe indirectly in superior animals. The majority of biologists dismiss these arguments as useless considerations. But again, once it is recognized on other bases that life transcends physics and chemistry, there is no reason not to recognize the obvious fact that consciousness is a principle which fundamentally transcends not only physics and chemistry but also the mechanistic principles of living beings."

Sign and Chance: Not All Chance Is Harmful

The great success of nineteenth-century quantum mechanics has introduced an irreducible aspect of indeterminacy into the laws of physics. In the face of this, Einstein's skeptical reaction, condensed into one of his most famous expressions, is well known: "God does not play dice." Einstein was very reluctant to admit that there was a degree of indeterminacy in the behavior of nature. Referring, for example, to the other great physicist Max Born, who argued for the principles of quantum mechanics, he clearly showed all his perplexity.

Albert Einstein[11]

We have become Antipodean in our scientific expectations. You believe in the God who plays dice, and I in complete law and order in a world which objectively exists, and which I, in a wildly speculative way, am trying to capture. I firmly believe, but I hope that someone will discover a more realistic way, or rather a more tangible basis than it has been my lot to find. Even the great initial success of the quantum theory does not make me believe in the fundamental dice-game, although I am well aware that our younger colleagues interpret this as a consequence of senility. No doubt the day will come when we will see whose instinctive attitude was the correct one.

The concept of "chance" is regarded by many, whether scientists or not, with suspicion and almost with repulsion. Chance is almost always mentioned as synonymous with nonsense: when it is established that a certain phenomenon is the fruit of chance, it is concluded that it has no further meaning. To say, for example, that life comes about "by chance" normally means that there is no need to add anything else: the question of its possible meaning and scope is superseded. If science could demonstrate that life was formed through random processes, there would be a tendency to conclude that the question of the presence of a Creator had been robbed of any content. This attitude is in reality somewhat strange, because it contrasts with the common experience that the more significant things in personal life, those with the deepest meaning, often happen "by chance," without having been programmed, or even foreseen at a distance either by us or by anyone else.

The position of Bertrand Russell, which is fascinating because of its radicality, shows how arguing for the total accidental character of things, with the tacit presupposition that "chance" is equivalent to a "lack of meaning," leads to an "unyielding despair."

Bertrand Russell[12]

That Man is the product of causes which had no prevision of the end they were achieving; that his origin, his growth, his hopes and fears, his loves and his beliefs, are but the outcome of accidental collocations of atoms; that no fire, no heroism, no intensity of thought and feeling, can preserve an individual life beyond the grave; that all the labours of the ages, all the devotion, all the inspiration, all the noonday brightness of human genius, are destined to extinction in the vast death of the solar system, and that the whole temple of Man's achievement must inevitably be buried beneath the débris of a universe in ruins—all these things, if not quite beyond dispute, are yet so nearly certain, that no philosophy which rejects them can hope to stand. Only within the scaffolding of these truths, only on the firm foundation of unyielding despair, can the soul's habitation be safely built.

Certainly it remains to be understood what is such a "firm foundation of despair" that one can build with certainty. Curiously, however, a similar point is arrived at starting from the diametrically opposite presupposition. Many scientists and much science have made progress on the principle that chance is in reality sheer illusion: the natural world is completely controlled by its own laws, which are of a deterministic and universal character. The present state of each individual corpuscle in the universe, as of their totality, depends solely and exclusively on the laws of physics and the precise conditions at any previous moment.

Pierre-Simon Laplace[13]

Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it—an intelligence sufficiently vast to submit these data to analysis—it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes.

Laplace's assertion implies that all that has happened in the universe, all that is happening now, and all that will happen has been unalterably determined from the first moment. The future can appear uncertain to our eyes, but it is already fixed in even the smallest detail. No action or human decision can change the destiny of a single atom, because we too are part of the physical universe.

In a world that is rigidly the slave of its laws, there seems to be no possibility of openness and of event. In a world that is continuously in motion, nothing new would ever occur—besides the purely apparent novelty due to our ignorance. The intelligence mentioned by Laplace that knows in a given instant the precise and complete configuration of the universe might be identified with the divine intelligence—but it should be noted that this deity would always remain a passive and impotent spectator of a world imprisoned in its blind mechanism (almost blinder than Bertrand Russell's accidental cosmos).

Ilya Prigogine, with a clear reference to Laplace, emphasizes the historical importance for science of such "determinist extremism," but this has had its time.

Ilya Prigogine[14]

The basis of the vision of classical physics was the conviction that the future is determined by the present, and therefore a careful study of the present permits the unveiling of the future. At no time, however, was this more than a theoretical possibility. Yet in some sense this unlimited predictability was an essential element of the scientific picture of the physical world. We may perhaps even call it the founding myth of classical science.

The situation is greatly changed today. ✺

Different new facts in science enliven the situation. Quantum mechanics and the study of chaotic systems have given a jolt to the deterministic approach and have begun to reveal to scientists of all disciplines aspects of nature hitherto unthinkable, which open up new perspectives of interpretation.

Douglas Hofstadter[15]

In 1981, while I was walking with a friend down the corridors of the Department of Physics of the University of Chicago, my eye fell on a notice which announced an international symposium under the title "Strange attractors." I could not fail to be drawn by this odd term and asked my friend what it was about. He replied that it was a very topical subject and from the description that he gave me it seemed to me to be indeed charming and full of mystery.

I understood that the basic idea was in the analysis of what could be called cycles of retroaction: cases in which the result of the calculation could be reintroduced as a new subject, just as sounds issuing from a loudspeaker can reenter the microphone and come out again. It seemed that from the simplest of these cycles could emerge either stable or chaotic structures (if the latter is not a contradiction in terms!): the difference lay in the value of a single parameter. The order or nonorder of the cyclical system depended on minuscule variations in the parameter and this image of order that vanishes gently into chaos, of a structure that dissolves and gradually becomes chance seemed to me to be fascinating.

It also seemed that there were recent appearances of unexpected "universal" characteristics in the transition to chaos, characteristics that depended uniquely on the presence of feedback and were virtually insensitive to other details of the system. This general feature was important because a mathematical model that shows a gradual approach to chaotic behavior could constitute the key to understanding the disappearance of turbulence in all types of physical systems. Turbulence, contrary to the majority of physical phenomena that have come to be understood, is a nonlinear phenomenon: two solutions to the equations of turbulence do not together lead to a new solution. The development of nonlinear mathematics is much inferior to that of linear mathematics, which is the reason that a mathematical description of turbulence has long escaped physicists, a description which, for obvious reasons, would be of fundamental importance.

When I went on to read something about these notions, I discovered that they were derived simultaneously from many disciplines. Students of pure mathematics had begun to concern themselves with the interaction of nonlinear systems using calculators. Students of theoretical meteorology and population geneticists, like theoretical physicists involved in different fields such as fluids, lasers, and planetary orbits, had independently arrived at nonlinear mathematical models of an analogous type, characterized by cycles of retroaction immersed in chaos: by studying the properties of these models each group found details that the others had not found. Moreover, not only the theorists, but also experimenters working within these very different disciplines, had simultaneously made observations on chaotic phenomena that denoted a basic common structure. It quickly occurred to me that the simplicity of the basic ideas gave them an elegance that rivaled that of some treatises of classical mathematics—that there is in fact, in some aspects of this work, a flavor of the eighteenth or nineteenth century which I find particularly pleasing in this era of impressive abstraction. ✺

Determinism seems to deny the mystery. Chance seems to deny design. Thus oscillating between these two extremes one often gets stuck in fruitless discussion. Is a universe governed by deterministic laws or one governed by unpredictable and irreducible events more open to the mystery? Is nature predominantly characterized by its chance aspect or nature predominantly characterized by its ordered aspect more the vehicle of a “sign”?

Hubert Reeves[16]

The reader of Monod will notice, however, that my vision of events differs from his. It is a question of interpretation. From biologists I have learned the facts. These facts have been acquired by means of a scientific technology that presents every appearance of objectivity. But the interpretation of these facts involves the entire person, including one’s logic, emotions, impulses, and prior experiences. Interpretation involves both observations and the observer. . . . To Monod, the essential role of chance in biological evolution proves the absence of any “intentionality” in nature. On this basis he denounces as illusory the ancient alliance of mankind with the universe; he sees man as an accident in a cold and empty cosmos, a child of chance. Indeed, but a child of bridled chance. Let us raise our hats to nature, which has tamed chance and made of it an admirable ally. ✺

It is evident that without the amazing character of “order” that the deterministic laws describe, the universe would be without continuity, incapable of complexity, completely incomprehensible. On the other hand, without the “capacity for event” introduced by chance, nature would be incapable of authentic newness and our perception of the world would lack real movement. Chance, sometimes somewhat disparaged by theology, presents itself to us through events whose cause escapes our knowledge. Any chance phenomenon is intrinsically unpredictable and cannot be reduced to antecedent factors.[17] It is not clear why the contingency and chance nature of phenomena must be felt to be in opposition to the realization of a purpose through the phenomena themselves, for example, in respect of biological evolution.

John Polkinghorne[18]

Certainly it was no longer possible to think of the complexity and fruitfulness of the living world as being the consequence of the execution of an inexorable divine blueprint in which it had been decreed from all eternity what should be the length of the giraffe's neck or what were the details of the optical system of the human eye. Something more flexible and innovative must now be considered as the story of life's coming to be and of its development. Yet it is not clear that the recognition of the role of a degree of historical contingency necessarily implies the complete denial of the discernment of purpose in what has been going on, though many modern biologists have wanted to impose that interpretation. Richard Dawkins wrote, "Natural selection, the blind unconscious automatic process which Darwin discovered, and which we know is the explanation for the existence and apparent purposeful form of all life, has no purpose in mind. It has no mind and no mind's eye. It does not plan for the future. It has no vision, no foresight, no sight at all. If it can be said to play the role of watchmaker in nature, it is the blind watchmaker." Yet, from the start, the matter has been seen to be more open to question than that. Charles Kingsley, an Anglican clergyman and contemporary of Darwin, welcomed the insights of evolution—for the popular myth of progressive science versus obscurantist Christianity is an historically ignorant account of the evaluation of Darwin's great discovery. Kingsley said that in the light of evolution scientists found that "they have got rid of an interfering God . . . and have to choose between the absolute empire of accident, and a living, immanent ever-working God." He saw that God had not just produced a ready-made world; he had done something cleverer than that in making a world that could make itself. A similar thought was expressed by his contemporary Aubrey Moore. Writing in Lux Mundi, he asserted that Darwinism, by making untenable the picture of a deistic intervening God, had "under the guise of a foe done the work of a friend." Instant creation had been replaced by the concept of a continuing creation. This idea still plays an important role in religious reflection on an evolutionary universe, finding a variety of expressions, as in the writings of Teilhard de Chardin and Arthur Peacocke.

Those who on the contrary wish to assert the "blindness" of evolution concentrate their attention on the undoubted contingency present in the process, as if that were the only aspect involved. They stress that mutations occur in ways that are not directly linked to survival needs. Yet these offerings of chance are selected by interaction with environmental necessity, in a process of remarkable fertility. It is possible to understand the shuffling explorations of possibility, which we choose to call "chance," as being a means for realizing, in contingent ways, something of the rich potentiality present in the necessity of natural laws. Evolution depends upon an interplay between chance and necessity and it is disingenuous not to consider the "lawful" side of what is going on.

There is an inexplicable affinity between human reason and the order that characterizes nature. But the "order" that we observe in the universe must not be confused with rigidity and immobility. It coexists with a good portion of "nonorder": nature flowers in its beauty, and in its complexity gives a delicate weave of laws and chance.

Paul Davies[19]

The most basic point is that the universe is ordered in the first place. Clearly it need not have been so. We can easily imagine a universe that is chaotic with varying degrees of severity. It is known, for example, that many systems subject to simple regular laws nevertheless display essentially random behavior. In the real world there are many examples of this form of chaos, but many important physical processes are nevertheless nonchaotic. There are also laws of physics with an irreducibly random (strictly, indeterministic) component. However, the uncertainty associated with these laws is largely restricted to the atomic realm, and is unimportant for most physical processes on an "everyday" scale. Finally, there is the extreme possibility of no proper laws at all, just random, arbitrary events.

At the other extreme, the universe could have been so highly ordered as to be essentially featureless. One can imagine a world consisting of nothing but empty space, or space occupied by an inactive crystal lattice, or a uniform gas. The actual universe is poised, interestingly, between the twin extremes of boring over-regimented uniformity and random chaos. Physical phenomena are constrained in an orderly way, but not so much as to prevent a rich and elaborate variety of physical systems to emerge and develop. The laws of physics preclude cosmic anarchy, but are not so restrictive as to rule out some openness in the way systems evolve. In short, nature employs an exquisite mix of order and chaos that seems almost contrived in its ability to achieve complex but organized activity. Indeed, some scientists have suggested that this mix may even conform to a sort of principle of maximal diversity.

Clearly, then, the universe is ordered in a very special sort of way. Were this not the case it is doubtful if conscious beings would exist to contemplate the fact. But there is something yet more remarkable about human consciousness. For we are not merely aware of the world about us. We are able, at least to a limited extent, to understand it. Human beings are able to discern the basic laws on which the universe runs, the very same laws that have facilitated the emergence of our consciousness in the first place. The laws are therefore doubly special. They encourage physical systems to self-organize to the point where mind emerges from matter, and they are of a form which is apprehendable by the very minds which these laws have enabled nature to produce. ✺

Both chance and the law appear indispensable features of the world of the senses. Both aspects can be understood and endorsed if they are seen as manifestations of a deeper reality, of a structure of the world of which both causality and randomness are products. Each of them, taken as the only key to look at the physical world, would lead to perdition: toward partial and grotesque views of nature that do not in fact accord with what we observe of it. There is a character in reality, which is perhaps even deeper and more elegant than one or the other—the indivisible unity between them. The proportions with which chance and causation are distributed in the universe may turn out to be one of the deepest structures that science could investigate.

Sign and Origin: Who Can Understand This Mystery?

Science does not have adequate structures for giving a complete answer to the question of the origin of reality. Scientific research is not equipped to deal with the question of the ultimate source of things: in fact, it can only describe a reality that is already there; it can only recognize the existence of things and describe their structure, behavior, change. One of the most typical procedures of scientific knowledge is to ask of the structures and phenomena that we observe, "where they come from," how they are formed, what is the history of their evolution. The scientist is so curious about things as to devote his life to attempting to going back up some branch of the river of time as far as he can. "The sun is there. Where does it come from?" Today we can say, "The sun comes from a cloud of gas and interstellar dust, and it was formed about five billion years ago." That is not an ultimate explanation; it is a contribution to our knowledge of reality. Along this route every partial response increases the perception of the inevitability of the radical question, "Where do things ultimately come from?" Every step of knowledge is a sign—a shadow, as it were—of this "strange" fundamental question.

The question "Where does it come from?" does not apply only to the sun or the earth but also to the cosmos as a whole. The discovery that the physical universe is not immutable but changing, historical, has literally overturned the idea that from antiquity human beings have had: the cosmos is no longer fixed and immutable but a reality that is changing every moment. The way the universe presents itself to us has radically shifted, with consequences that probably have not yet come into equilibrium with our perception, and which still have not become part of our feeling about things.

Hubert Reeves[20]

That the universe had a history was a completely foreign idea to the scientists of earlier centuries. Immutable in their eyes were the laws of nature that governed the properties of matter in an eternal present. Changes such as birth, life, and death, observable in our daily lives, were explained in terms of a multitude of simple atomic reactions, themselves immutable. Matter simply had no history.

In his beautiful book on bees,[21] the Belgian writer Maurice Maeterlinck rhapsodizes over the organization of the hive. But his enthusiasm turns to pessimism at the end when he ponders the meaning of nature and its future: "It is foolish to wonder where things and worlds are going. They are not going anywhere, and they have arrived. In a hundred billion centuries, the situation will be just the same as today, just as it was a hundred billion centuries ago, just as it has always been since a beginning which never was and always will be, until an end which is equally nonexistent. There will never be anything more, anything less, in the material or spiritual universe. . . . One could perhaps cite an experience or proof which served a useful purpose, but having traversed eternity merely to arrive at this point, does not our world demonstrate that experience is worth nothing?"

The German philosopher G. W. F. Hegel expresses the same view of things in his famous saying, "Nothing new ever happens in nature." ✳

Today science has made this claim to demonstrate the uselessness of everything rather remote and irrational. Far from "nothing new ever happens in nature," at every level the natural world appears to the modern scientist as an extremely dynamic reality, capable of events and authentic newness.

When scientists use the word "origin" in their language, they have to do so with full awareness. Observation and experimentation, on which necessarily rest the whole span of scientific knowledge, presuppose an existing reality: we cannot describe something that is not. Thus, through scientific cosmology we can describe the behavior of the universe, from within time, but not the way in which it came into being. To describe the universe after a fraction of a second from the "beginning" is infinitely different from claiming to describe its origin. And if some current cosmological theories speak of "spontaneous creation of the universe from nothing," they are in fact playing (sometimes perhaps not innocently) on the linguistic ambiguity of the word "nothing" or "void" between physics and metaphysics. The "nothing" of physics, the "quantum vacuum" whose fluctuations might represent the first structure of reality conceivable for us today, is a radically different concept from the "nothing" of metaphysics. For physicists to speak of that "vacuum" means to speak of things that are "fuller" and richer than can be imagined: a level of minimum energy that, however, potentially contains the seeds of the extraordinary complexity of the constituents of the universe and its structures.

But there is a way of understanding the word "origin" that is more radical and more profound than that typical of scientific language: "What brought the sun into being?" "Where does it ultimately come from?" Creation is not a fact relegated to a past 14 billion years ago: it expresses the radical dependence, now and in every moment, of the creature on the Creator. In this sense, even if we discover that the structure of the universe is such as to allow, in some sense, an indefinite time in the past, as Stephen Hawking hypothesizes, this would not be in any fundamental conflict with the idea of creation. On the other hand, it is known that George Lemaître, a Catholic priest and father of the big bang theory, tried to moderate the enthusiasm of Pope Pius XII in order to avoid his appreciations of the new cosmological discoveries being interpreted as a supposed scientific demonstration of creation.[22]

Stephen Hawking[23]

Throughout the 1970s I had been mainly studying black holes, but in 1981 my interest in questions about the origin and fate of the universe was reawakened when I attended a conference on cosmology organized by the Jesuits in the Vatican. The Catholic Church had made a bad mistake with Galileo when it tried to lay down the law on a question of science, declaring that the sun went round the earth. Now, centuries later, it had decided to invite a number of experts to advise it on cosmology. At the end of the conference the participants were granted an audience with the pope. He told us that it was all right to study the evolution of the universe after the big bang, but we should not inquire into the big bang itself because that was the moment of Creation and therefore the work of God. I was glad then that he did not know the subject of the talk I had just given at the conference—the possibility that space-time was finite but had no boundary, which means that it had no beginning, no moment of Creation. . . .

George V. Coyne[24]

The key to understanding the difference between creation and cosmological origins is the notion of "change." The object of the natural sciences is the world of things that change: from the fluctuations of the quantum void to quarks, to hydrogen, to galaxies. Every time there is a change, there must be something that changes. Nothing comes from nothing, if the verb "come" signifies a change. Each change requires some underlying material reality.

There is no necessary conflict between the doctrine of creation and any cosmological theory. The theories of the natural sciences take account of change. Whether the changes described are cosmological or biological, whether or not they have a beginning, whether they are temporally indefinite or finite, they remain simply processes.

. . . To create is to give existence, and all things depend on God for the fact that they are. It does not take "nothing" to make something "of it." Rather, anything left entirely to itself, separated from the cause of its existence, would be absolutely "nothing." Creation is not exclusively, nor even primarily, a certain distant event. The creative act of God is the continual, complete causation of existence as it is.

It is said that God creates from nothing. There is a persistent confusion between the concept of "nothing" in cosmology and in metaphysics. The "void" of particles in modern physics, whose "fluctuations" could have generated our present universe, is certainly not to be confused with nothingness. It certainly will not be something like our present universe, but it is always "something." How otherwise could it "fluctuate"? The "nothing" of contemporary cosmological theories in reality proves to be "something," whereas the notion of "nothing," central to the theological and metaphysical conception of creation from nothing, is radically different from the various notions of "nothing" used in contemporary scientific cosmological discourse. To speak of "creation from nothing" means that one denies that other material is changed or transformed into something else. The expression "from nothing" is at root the negation of some material cause in the act of creation.

To argue that the universe does not have a beginning (whether because it is eternal, as the ancients thought, or because the very notion of temporality is a subsidiary concept, as Hawking thinks) does not clash with the fundamental metaphysical truth that the universe is created. . . . Even if the universe did not have a temporal beginning, it would continue to depend on God for its very existence. The radical dependence on God as the cause of being is what "creation" signifies. ✺

For that reason the evidence that the universe had a primordial phase with extremely simple conditions is not "proof of creation"; rather, it makes more dramatic and inevitable a question about the ultimate origin of the real. The historicity of the cosmos and its surprising past are an amazing sign of that radical dependence of the contingent real on the "other." We are in a situation in which by following a strictly scientific course, and looking at reality without censoring its breadth and riches, one is led to the threshold of questions that clearly go beyond the capacity of science itself.

The fact remains that the appearance in the scientific community of the prospect of a time "finite in the past" was not a peaceful one. The following passage is a fragment from one of the many accounts of the circumstances that revolutionized cosmology from the 1920s on. In the 1970s Robert Jastrow, a scientist and journalist, gave an effective account of the climate of trepidation, embarrassment, and sometimes irritation that the idea of a universe with an origin introduced among many scientists.

Robert Jastrow[25]

Five independent lines of evidence—the motions of the galaxies, the discovery of the primordial fireball, the laws of thermodynamics, the abundance of helium in the Universe and the life story of the stars—point to one conclusion; all indicate that the Universe had a beginning. In the past, a few scientists bit the bullet and dared to ask, "What came before the beginning?" Edmund Whittaker, a British physicist, wrote a book on religion and the new astronomy called *The Beginning and End of the World* in which he said, "There is no ground for supposing that matter and energy existed before and was suddenly galvanized into action. For what could distinguish that moment from all other moments in eternity?" Whittaker concluded, "It is simpler to postulate creation *ex nihilo*—Divine will constituting Nature from nothingness."

Some scientists were even bolder, and asked "Who was the Prime Mover?" The British theorist, Edward Milne, wrote a mathematical treatise on relativity which concluded by saying, "As to the first cause of the Universe, in the context of expansion, that is left for the reader to insert, but our picture is incomplete without Him."

But the views of most physicists and astronomers remained closer to that of Saint Augustine, who asking himself what God was doing before he made Heaven and Earth, gave the reply, "He was creating Hell for people who asked questions like that." In fact, some prominent scientists began to feel the same irritation over the expanding Universe that Einstein had expressed earlier. Eddington wrote in 1931, "I have no axe to grind in this discussion" but "the notion of a beginning is repugnant to me. . . . I simply do not believe that the present order of things started off with a bang. . . . The expanding Universe is preposterous . . . incredible. . . . It leaves me cold." The German chemist, Walter Nernst, wrote, "To deny the infinite duration of time would be to betray the very foundations of science." Phillip Morrison of MIT said in a BBC film on cosmology, "I find it hard to accept the Big Bang theory; I would like to reject it." And Allan Sandage of the Carnegie Observatories, who established the uniformity of the expansion of the Universe out to nearly ten billion light years, said, "It is such a strange conclusion . . . *it cannot really be true*." (The italics are mine.)

There is a strange ring of feeling and emotion in these reactions. They come from the heart, whereas you would expect the judgments to come from the brain. Why? I think part of the answer is that scientists cannot bear the thought of a natural phenomenon which cannot be explained, even with unlimited time and money. There is a kind of religion in science; it is the religion of a person who believes there is order and harmony in the Universe. Every event can be explained in a rational way as the product of some previous event; every effect must have its cause; there is no First Cause. Einstein wrote, "The scientist is possessed by the sense of universal causation."

This religious faith of the scientist is violated by the discovery that the world had a beginning under conditions in which the known laws of physics are not valid, and as a product of forces or circumstances we cannot discover. When that happens, the scientist has lost control. If he really examined the implications, he would be traumatized. As usual when faced with trauma, the mind reacts by ignoring the implications—in science this is known as "refusing to speculate"—or trivializing the origin of the world by calling it the Big Bang, as if the Universe were a firecracker.[26]

In a different context, the great physicist James C. Maxwell makes the crucial point—science stops at the fact that every molecule of the universe is not made by itself (it is "held in being" by something else). And this "giving being" is not among the natural processes investigated by science.

James Clerk Maxwell[27]

Thus we have been led, along a strictly scientific path, very near to the point at which Science must stop. Not that Science is debarred from studying the internal mechanism of a molecule which she cannot take to pieces, any more than from investigating an organism which she cannot put together. But in tracing back the history of matter Science is arrested when she assures herself, on the one hand, that the molecule has been made, and on the other, that it has not been made by any of the processes we call natural.

Science is incompetent to reason upon the creation of matter itself out of nothing. We have reached the utmost limit of our thinking faculties when we have admitted that because matter cannot be eternal and self-existent it must have been created.

It is only when we contemplate, not matter in itself, but the form in which it actually exists, that our mind finds something on which it can lay hold.

That matter, as such, should have certain fundamental properties—that it should exist in space and be capable of motion, that its motion should be persistent, and so on, are truths which may, for anything we know, be of the kind which metaphysicians call necessary. We may use our knowledge of such truths for purposes of deduction, but we have no data for speculating as to their origin. ✺

Sign and Mystery: Taking a New Look at the World

Modern science allows us to approach the boundaries of reality under different perspectives. We are in a position to observe galaxies and quasars that are tens of billions of light years away, and our instruments explore even farther the most remote regions of the accessible universe, from which the fossil light of a cosmos in its first infancy reaches us. We are in a position to understand, at a surprising depth, what happens in the intimate structure of matter, descending within individual particles that compose the nuclei of atoms. We can describe with remarkable precision physical phenomena that happen at very high temperatures (or energies), far beyond any possible contact with our direct experience. At the same time, technology allows us to study in detail the opposite situation, that is, the behavior of matter near to "absolute zero," down to temperatures so low that they are never reached in nature and which only in the remotest of futures could characterize the emptiest regions of the universe.

Together with the marvel of what is given to us to know, in different ways the sign emerges of the frontier of what is within our scope. Physical reality, but also mathematical reality, infinitely exceed the things that we understand of them. And we can wager that this will also be the case in future, however prodigious the progress of science may be. The researcher is therefore familiar with a certain form of "mystery," not only understood as "what we still do not know," but in the sense of a reality that radically escapes our capacity for definition and comprehension. Ennio De Giorgi explains that in mathematics the reference to such an "unknowable" level is essential for dealing with what is known.

Ennio De Giorgi[28]

Every time an organization of mathematics is attempted (from within), one is confronted with insuperable difficulties and, in substance, encounters a certain form of mystery. Working as a mathematician, I am led to accept that not only the things that exist are, as is obvious, more than I know, but that to be able to speak of things that are known I am forced to refer to unknown things which are in fact beyond the scope of human knowledge; I never succeed in delimiting two zones, one of perfect clarity and one of total obscurity; the boundary between things that are known or can be known and things which are unknown and cannot be known is always uncertain.

Encountering a form of mystery already in the reality of his science, the mathematician cannot wonder at encountering it again in a much higher reality like that of religion: therefore the fact that religion anticipates mystery seems to him a necessary condition for his credibility rather than an obstacle in accepting it. One could say that for a mathematician a religion without mystery would be evidently false.

It is difficult in a few words to illustrate the "mysterious" character of the foundations of mathematics (which moreover has been brought out above all by the most advanced logical researches of this century). I shall limit myself to noting that in mathematics, even if one wants to limit oneself to finitistic procedures, one has to accepts rules of a nonfinitistic kind. For example, an addition of two integers is an operation that is done with a limited number of steps, but to define the addition one is forced to speak of the (infinite) totality of natural integers.

In general, the description of certain objects can be made only by accepting quite complex rules of the objects to be described. Every time one wants to describe a formal system of a certain potency one needs a rather more superior potency. Those who study mathematics know that there are different levels of infinites: the discussions of "small" infinites can fit in well only if one has trust in the "greater" infinites, just as faith in the finitistic part of mathematics is bound up with faith in the infinitistic part!

Discourse of this type is now often called "metamathematics." One can ask whether there is any relationship between mathematics and metaphysics and whether the discovery of the incapacity for "self-description" and "self-justification" in mathematics necessarily bears on the acceptance of traditional metaphysics. This is a difficult discussion given that, whereas on the one hand most recent mathematical research is leading to a revaluation of a realistic conception of knowledge (the correspondence between concepts or propositions and reality), on the other hand it brings out serious logical difficulties which are obstacles to the formulation of systems capable of a complete self-description. In mathematics, logical and formal systems that comprise negation among their categories cannot be self-descriptive; perhaps difficulties of the same kind, even if they are hidden in various ways, can also be met in many philosophical systems, but to bring them out would need a simultaneous and equally profound knowledge of philosophy and mathematical logic which it is difficult to attain.

. . . Science, art, philosophy can still be considered as "handmaids of theology," handmaids, at any rate, which are not indispensable because faith cannot do less and indeed can give full meaning to the toil of those who work in the fields of science, philosophy, or art. For example, it is easier for those who believe to accept the fundamental principle of scientific ethics, that is, passionate research for the truth, which has to prevail over any interest of a pragmatic kind (the scientist as a technician in the service of the power or as a propagandist in the service of ideology).

Only if scientists love and investigate the truth as a good that is desirable in itself can they also serve the global interest of humanity, since the truth is liberating both in the spiritual and the material order, whereas mystification enslaves.

The mystery is not in the "gaps" in science; it is not the territory of ignorance that retreats under the blows of advancing scientific discovery. On the contrary, the mystery lies first and foremost in the very fact that this reality exists, in the way in which it is made and in that to which it relates. Therefore, science contributes toward bringing to light reality as a sign of the very mystery in doing what it has to do: attempting to unveil the secrets of the fabric of the physical world, discovering its laws, bringing to light the order within nature, its variety, beauty, unity, fertility, direction.

The reality of the mystery emerges in the smallest observation as in the most elaborate scientific theory. The very "reference to another" is irresistible, whether one is studying the properties of electrons or investigating the human brain. The neurophysiologist and Nobel Prize–winner John Eccles, having spent his life investigating human evolution and the relationship between mind and brain, rejects the idea of an explanation of human beings in purely materialistic terms, just as he is not persuaded by the idea of a cosmos that rotates "perennially without meaning."

John Eccles[29]

I accept all of the discoveries and well-corroborated hypotheses of science—not as absolute truth but as the nearest approach to truth that has yet been attained. But . . . there is an important residue not explained by science, and even beyond any future explanation by science. . . .

If I should be asked to express my philosophical position, I would have to admit that I am an animist on Monod's definition. As a dualist I believe in the reality of the world of mind or spirit as well as in the reality of the material world. Furthermore I am a finalist in the sense of believing that there is some Design in the processes of biological evolution that has eventually led to us self-conscious beings with our unique individuality; and we are able to contemplate and we can attempt to understand the grandeur and wonder of nature. . . . But I am not a vitalist in the generally accepted sense of that term. I believe that all of the happenings in living cells will be found to be in accord with physics and chemistry, much of which has yet to be discovered. Yet, as I have already stated, I believe with Polanyi that there is a hierarchic structure with emergence of higher levels that could not have been predicted from the operations going on at a lower level. For example the emergence of life could not have been predicted even with a complete knowledge of all happenings in a prebiotic world, nor could the emergence of self-consciousness have been predicted.

My aim in these lectures is to review the sense of wonder and of mystery in our human existence. We must not claim to be self-sufficient. If we espouse the philosophy of monist-materialism, there is no base on which we can build a meaning for life or for the values. We would be creatures of chance and circumstance. All would be determined by our inheritance and our conditioning. Our feeling of freedom and of responsibility would be but an illusion. As against that I will present my belief that there is a great mystery in our existence and in our experiences in life that is not explicable in materialist terms. This residue is beyond all else the ultimate value of our world. . . . The whole cosmos is not just running on and running down with no meaning. Furthermore, I will suggest . . . that we are creatures with some supernatural meaning as yet ill defined. We cannot know more than that we are all part of some great design. ✺

To consider the possibility of such a "design" is equivalent to asking whether the physical phenomena that we are in a position to observe, measure, and to some degree comprehend are the visible features of a deeper reality that surpasses them, or whether they are to be registered without any other significance than their sheer existence. The question is inevitable: not to accept the possibility that the physical world relates to a deeper level of reality is the equivalent of denying the possibility of a meaning. And sometimes even those who assert that such questions are our inventions are basically nostalgic for such a full and total meaning.

Steven Weinberg[30]

In my 1977 book, *The First Three Minutes*, I was rash enough to remark that "the more the universe seems comprehensible, the more it seems pointless." I did not mean that science teaches us that the universe is pointless, but rather that the universe itself suggests no point. I hastened to add that there were ways that we ourselves could invent a point for our lives, including trying to understand the universe. But the damage was done: that phrase has dogged me ever since. Recently Alan Lightman and Roberta Brawer published interviews with twenty-seven cosmologists and physicists, most of whom had been asked at the end of their interview what they thought of that remark. With various qualifications, ten of the interviewees agreed with me and thirteen did not, but of those thirteen three disagreed because they did not see why anyone would expect the universe to have a point. The Harvard astronomer Margaret Geller asked, ". . . Why should it have a point? What point? It's just a physical system, what point is there? I've always been puzzled by that statement." The Princeton astrophysicist Jim Peebles remarked, "I'm willing to believe that we are flotsam and jetsam." (Peebles also guessed that I had had a bad day.) Another Princeton astrophysicist, Edwin Turner, agreed with me but suspected that I had intended the remark to annoy the reader. My favorite response was that of my colleague at the University of Texas, the astronomer Gerard de Vaucouleurs. He said that he thought my remark was "nostalgic." Indeed it was—nostalgic for a world in which the heavens declared the glory of God.

Sign and Design: In the Auto Body Parts Shop

In recent decades science has unexpectedly brought to light that we live in an absolutely special universe. The laws of physics, and in particular the value that the fundamental constants of nature assume, model the structure of the universe and play a central and very delicate role in the establishment of the global conditions that have allowed complexity and life to emerge. Imagine that we have a fantasy instrument with controls that allow us to regulate the constants of nature to our liking: it would be very difficult to brush against any of the controls, slightly varying the value of a constant of nature, without causing an irreparable cosmic disaster. We could not exist in a universe in which, for example, the relations between the intensity of the fundamental forces (gravitation, electromagnetism, weak and strong forces) would also be slightly different from what we observe. Similarly, *a priori* it could be thought that the velocity of light or Planck's constant have little to do with our life and with the complexity of the world; these constants establish the principal characteristics of the macrocosm and the microcosm. If it were to assume values even slightly different from those that they have, the universe as a whole would present itself as radically different from what it is. And the cosmos would almost certainly be inhospitable to life and incapable of fertility. A great deal has been written and debated on this topic (often listed under various forms of the so-called anthropic principle),[31] and this is certainly not the place for an exhaustive discussion; however, one cannot do less than note that this factual evidence has reopened questions and horizons in the scientific debate that seemed a century or so ago to be sealed forever.

John Polkinghorne[32]

In our scientific imaginations we can consider universes similar to ours but differing in some aspects of their physical fabric. One of the simplest variations to consider would be one in which the intrinsic strength of one of the forces of nature was different from the value it takes in our universe. For example, one could make the fine structure constant α (which measures the strength of electromagnetism) different from our value of about 1/137. I would have guessed that this change would have no drastic effect on the history of that other world. If α were bigger, matter would be more dense (it is electromagnetism that holds bulk matter together), so the "people" of that world would be chunkier. But I would have expected that the evolutionary history of that universe would have produced its own kind of life—not *Homo sapiens*, of course, but maybe little green men. I would have been mistaken! A universe of that kind would have had a boring and sterile history. Evolution by itself is not enough. You cannot, if you want to fulfil the role of Creator, simply bring into being more or less any old world and just wait a few billion years for something interesting to happen. Only a very particular, a very "finely tuned," universe is capable of producing systems of the complexity and fruitfulness to make them comparable to anthropoi. The interplay of chance and necessity requires the necessity to have a very special form if anything worthy (by our standards) to be called "life" is to emerge. It is this surprising conclusion that has been called the Anthropic Principle.

It is worth looking in some detail at why a fruitful universe is thought to have to be so special in its physical constitution. Many reasons can be given and I shall only attempt to indicate something of the range of considerations involved.

In the first instance one needs to have the right kind of physical laws. Nature must not be too rigid, or else there will not be scope for the kind of flexible change that is the engine of evolution. Equally, nature must not be too floppy, or else there will be no persistence in the novel forms of organization that come into being. Quantum mechanical laws provide just that basic opportunity for the interplay of chance and necessity that seems essential for fertile development.

Next, the intrinsic force strengths need to lie within very narrow limits. The most striking example of this is the cosmological constant. It corresponds to a term that logically can be present in the field equations of general relativity (the modern theory of gravity) but appears to be absent in our world to the extent that its value is zero to within one part in 10^{120}. Were the cosmological constant not virtually zero to this high degree of accuracy, that would make the evolution of life impossible, either by producing instantaneous cosmic collapse (if its sign were negative) or by inducing extremely rapid expansion and consequent dilution (if its sign were positive). This is the most stringent of all the anthropic requirements and it can result only from an exquisite degree of cancellation between two contributions that combine to produce the total effect.

Less exacting, but still tight, limits apply to the other forces of nature. Take electromagnetism. The nature of chemical bonding requires that it be not significantly weaker than it is, yet, if it were somewhat stronger, rates of chemical reactions would be appreciably slowed down and the evolution of life correspondingly retarded. There are many detailed properties of matter that depend on the electromagnetic force and have anthropic consequences. Crucial to the possibility of life in the waters of Earth is the remarkable property that ice is lighter than water, so that freezing takes place from the top downwards and not from the bottom upwards. In consequence, ice forms a skin on the surface, which easily melts at warmer temperatures and which protects the aquatic creatures living underneath while frost endures. A lake solidified from the bottom up would take a long time to melt and it could not be expected to sustain life.

Gravity must be strong enough to cause stars and galaxies to condense, but not so strong as to enforce a cosmic collapse. A particularly sensitive balance between gravity and electromagnetism controls the way in which stars burn (producing long-lived stable sources of energy, essential for the development of life). If electromagnetism were only slightly stronger than it is in relation to gravity, all stars would be red and probably too cold for supporting life; if electromagnetism were relatively slightly weaker, all stars would be blue, intensely hot, and they would live for only a few million years—far too short a time for an evolutionary history to develop on one of their planets.

There are two sorts of nuclear force at work in our universe: the strong nuclear force that holds nuclei together and the weak nuclear force that causes some of them to decay. The latter played an important role in early cosmic history. If it had been significantly stronger, hydrogen would have readily burnt to helium and only that element would have been left to constitute the galaxies and stars as they began to condense. There would then have been no water and no hydrogen-burning stars, which, we have noted, alone give the stable long-lived sources of energy needed for the development of life. If, on the contrary, the weak force had been a little weaker there would then have been no hydrogen left over after those hectic first three minutes in which the whole universe was hot enough to be the arena of nuclear reactions. The survival of some hydrogen requires an excess of protons over neutrons, which is derived from the decay of neutrons into protons, and a feebler weak nuclear force would have made that too slow a process to be effective. The strong nuclear force also has its anthropic bounds: a little stronger and protons would bind to form the diproton (again, no hydrogen); a little weaker and the deuteron becomes unbound, with disastrous consequences for the nuclear processes that make stars burn.

The nuclear processes in the stellar furnaces do not only provide energy. They also make the heavier elements, essential for the chemistry of life. We are made from the ashes of dead stars! Both of the nuclear forces play finely tuned roles in the delicate story of nucleosynthesis. The strong force is such that there is an enchancement (a resonance) in just the right place to enable three helium nuclei to stick together and make carbon. Fortunately, there is not another such enhancement present in the process whereby a further helium nucleus can stick to the carbon to make oxygen. This has the result that some oxygen is made but some carbon is also left behind. (It would be anthropically disastrous to turn all the carbon into oxygen.)

The weak nuclear force plays an essential role in the way some stars explode as supernovae (thus scattering their previous nuclear products out into the environment, where they can become part of the chemical composition of second-generation planets) and at the same time make essential heavier elements (such as zinc and iodine) that cannot be created in stellar interiors.

The sequence of reactions involved in synthesizing the range of nuclei needed for life is extremely complex and delicately balanced. Its unraveling has been a major achievement of twentieth-century physics. . . . ✺

The English astrophysicist Fred Hoyle discovered the thermonuclear reactions that synthesize the nuclei of carbon and oxygen within the star cores. The production of such elements, without which biological complexity would be impossible, is obtained in nature thanks only to a very fine and apparently chance combination of resonances in the levels of energy of the nuclei of carbon and oxygen. Hoyle comments on how this circumstance is strictly bound up with the possibility of life on the universe.

Fred Hoyle[33]

I do not believe that any scientist who examined the evidence would fail to draw the inference that the laws of nuclear physics have been deliberately designed with regard to the consequences they produce inside stars. If this is so, then any apparently random quirks have become part of a deep-laid scheme. If not then we are back again at a monstrous sequence of accidents. ✺

The very fact of noticing that the conditions for life and for our existence depend in such a fine and dramatic way on the cosmic structure and its laws has led and is leading scientists to ask about a broader sphere than that usually allowed to scientific discussion. It is the rediscovery in a modern key of a unity, possible and now forgotten for centuries, between the human body and cosmic reality. And unexpectedly a possible new clue of a goal, or direction, in nature has arisen.

John Archibald Wheeler[34]

"Imagine a gigantic auto body part shop that has parts for every automobile ever made," Wheeler said. "Stacked up on the big field are auto fenders of the earliest Ford over in a corner, then as the Ford evolved, the shape of the fender began to change a little, so those altered fenders are stacked a little further along in the field. The man who has the miserable job of locating all the parts has had the wit to place them so that fenders of nearly the same shape lie at nearly the same position, so they can be found easily. This big field would be superspace, and the automobile fenders the various geometries of space."

The cosmic fireball might have dealt a wildly different universe than the one we inhabit, with an alien geometry and different physical laws; many of the universes possible in superspace never form stars, planets, or even atoms and molecules. This brings us, by a variant route, to a point we have considered before, that we owe our small existence to that of the broad universe. It suggests, in Wheeler's words, "that there exists a degree of harmony between us and our surroundings that we never realized before. In the past, we looked at our surroundings as if there could be no other, something with which we just had to get along. If this new view is correct, our surroundings are very special and tuned to us, like a plant to its flower: This cycle of the universe is like the plant, and we are like the flower.

"At first this theoretical prediction seems like the most esoteric thing in the world. But recall: there was a time when we thought of a piece of wood as solid; then we learned to think that it's 99.9 percent empty space and that it derives its solidity from electrons whirling around. And now we dare to speak about the possibility that the electrons themselves are, in some sense difficult to be specific about, also made of empty space; or, rather, space that is changing, dynamic, altering from moment to moment." ✺

So cosmic evolution has led to conditions in which life is possible. But the traces of a direction, of a destination, in nature do not end here; indeed this appears to be a new starting point. In the historical circumstances of the evolution of life on our planet, we can recognize the presence of an ordered dimension, guided by natural laws such as those of genetics; these, together with a chance and irreversible component, make our biological reality intrinsically open. As Hubert Reeves has written, paraphrasing Einstein, "Certainly God plays dice. But he makes only winning throws."

Edoardo Boncinelli[35]

Today it is known that the genetic code with which biological instructions are written is the same for all organisms and that the mechanism through which the synthesis of proteins is realized, along with the external structure of the cellular membrane and the biochemical bases of the metabolism, are the same or almost the same in every organism. Recently it has also been discovered that many genes are the same in the most diverse organisms and function according to the same logic. In sum, life is one and seems to derive from a single matrix, the essential features of which we can work out. That clearly contrasts with the enormous variety of internal organisms and the bodily arrangements of the various organisms.

The most important genes, those which provide stability—for example, the form and the subdivision of the body—are the same in earthworms, butterflies, frogs, and human beings. Even if we are led to give priority to the revolutionary aspect of biological evolution, it is noted that this is possible because the genetic patrimony is extremely conservative in its essence. The regulatory genes of a high hierarchical level, those which establish the subdivision of the body, are the same in all organisms. In all superior organisms, first comes the head, then the thorax, and finally the abdomen. It seems a banal observation, but no one has ever seen an organism with the head between the thorax and the abdomen. Why? Because the genes that establish the position of the head, the thorax, and the abdomen are always the same and are located in the same order in a particular genomic region of every organism. The whole biological variability is based on an exceptional constancy of the project. And it is this constancy which allows the incredible variety that we observe.

Biological evolution is the most concrete and tangible illustration of the irreversibility of time, understood as an uninterrupted sequence of breaks in symmetry. The *break in symmetry* is the process by which two objects which at first are indistinguishable become distinguishable and distinct. That has happened and happens continually even in the inanimate world. It took place at the beginning of the physical world and happens every time a galaxy, a star, or a planet is formed. We can in fact conceive of the separation of the earth from the sun and the other planets as a break in symmetry, one of many. These breaks in symmetry take place all over the known universe, but are evident and almost palpable above all in the biological sphere. Perhaps it is a matter of emphasizing how biology, once so much the Cinderella of the sciences, has also taught something to physics. A century ago no one knew that the universe was evolving in its complexity; today this is an almost ordinary concept.

At any rate biological evolution represents the maximum of irreversibility, of unpredictability, and therefore of creation in time. It is an uninterrupted production of newness. No one can foresee what will happen, just as no one could have foreseen what has happened. No one "projects" newness. It originates under the thrust of the internal generation of mutations and is selected by the external environment according to criteria which we are not always in a position fully to understand. Why does one species spread and another become extinct? Because the arrival of rabbits in Australia profoundly changed its fauna? Because carnivores with placentas supplanted marsupial carnivores? More or less probable explanations can be found for all these events, but I challenge anyone to predict them. Biological evolution is by definition an open phenomenon.

Whereas for the physicist and the cosmologist even considering the possibility of a direction or destination of the physical world may appear almost as the violation of a taboo that was maintained for a long time, for the biologist it is normal to consider the presence of the category of "purpose" or "goal" so that it has returned into the very definition of the living being.

Jacques Monod[36]

One of the fundamental characteristics common to all living beings without exception [is] that of being objects endowed with a purpose or project, which at the same time they exhibit in their structure and carry out through their performances (such as, for instance, the making of artifacts).

Rather than reject this idea (as certain biologists have tried to do) it is indispensable to recognize that it is essential to the very definition of living beings. We shall maintain that the latter are distinct from all other structures of systems present in the universe through this characteristic property, which we shall call *teleonomy*.

The evidence of a profound relationship between the life and the structure of the universe, however one wants to interpret it, unexpectedly leads to the threshold of a rediscovered unity of the cosmos, an order of nature that is not just mechanical.

That reopens the question: is this the sign of a direction of the universe toward living organisms and self-aware beings? The question—whatever the answer—raises itself in an almost inevitable way.

Victor F. Weisskopf[37]

It [the story of evolution] is a development from the simple to the complicated, from unordered chaos to highly differentiated units, from the unorganized to the organized. This trend, however, is not shared by all matter in the universe; the more developed areas are much smaller than the less developed ones. Only a small part of the hydrogen cloud is able to form stars; in a small part of the star (the inner part), hydrogen is transformed into heavier elements. Only a small part of these elements is ejected into space, and only a small fraction of the ejected matter assembles in the form of a planet near a star. A small fraction of all planets is sufficiently near but not too near to the star, so that water stays liquid and chemical reactions can occur. Only a very small part of matter on these planets forms the long chain molecules that are the basis of life, and only a small part of all living matter develops a brain.

Every step to higher differentiation in this development requires an abundant amount of less differentiated material. The nuclear oven in the center of the star would not be hot enough for the production of elements were it not surrounded by vast amounts of hydrogen. Life on Earth requires radiant heat that can be supplied only by a much larger body, the sun—whose material is in a more primitive stage—since no molecule can exist at a high temperature.

. . . The vastness of the universe, the billions of stars and the space between them are necessary conditions for the development of matter from simple, unordered particles, to atoms and molecules, and finally to the large aggregates that form animals and sentient beings. The spots at which matter acquires more differentiated shape are very few and selected. They must be considered as the most developed and most outstanding parts of the universe, the parts where matter was able to make fuller use of its potentialities. We find ourselves, therefore, in a very privileged and central position, since our Earth is one of these spots. There might be other places where the development has gone much further even than here, but on the earth's surface life has developed and produced a thinking species. Nature is reflected in the thoughts of these beings. ✺

Both the previous passage from Victor Weisskopf and the subsequent passage by Nicolò Dallaporta seem to echo the famous Pensée of Pascal, enriched by three centuries of greater scientific knowledge.

Blaise Pascal[38]

All bodies, the firmament, the stars, the earth and its kingdoms, are not comparable to the mind at its lowest; for the mind knows it all and knows itself; and bodies know naught of it.

All bodies together, and all minds together, and all their works, are of less worth than the smallest act of charity. Charity is of an infinitely higher order.

From all bodies together we cannot extract one little thought; it is impossible, and of a different order. From all bodies and minds we cannot extract a single impulse of charity; it is impossible, and belongs to a different and supernatural order. ✺

Nicolò Dallaporta[39]

The stars form the heavy elements from which one day the earth came into being and then the whole world of organic molecules, of organized beings, of vegetation, animals, and finally human beings. All the beings important for our life are a distant by-product of stellar evolution. Because it is fixed solely on the bodily world, this observation could lead to reckoning that the human being is insignificant by comparison with the stellar cosmos.

On the other hand, it is precisely in this corporeal insignificance that human subjectivity is incarnate, the faculty by which a similar particle is capable of saying: I see, I feel, I breathe, I am, I think, and I understand the picture of this material cosmos at the ultimate level of which I am placed. However, one could ask where was the essential of this cosmos, the ultimate *raison d'être* for what has been conceived and constructed: in the immense stars, in those colossal passings-away of pure matter, or in that ultimate by-product of their evolution? Can one banish the suspicion that such an immensity of cosmic forces has been set in motion in order to arrive solely at this lowly by-product, and that the cosmic games of matter took place with their main function that of providing adequate support for the entry of subjectivity also into the world of bodies? Or that what is great in the cosmos is small in the domain in which subjectivity has prevailed and vice versa? And that, overturning the relationship between bodily and subjective, the first must be the last and the last first?

The whole cosmos seems to me to affirm this gospel truth in a peremptory way. ✺

Sign and Purpose: Why Are the Laws as They Are?

Human intelligence is capable of grasping natural reality as a sign of something to which it tends: the universe expresses and allows us to see a "Thou" who has created it. The awareness that the natural world is a sign of mystery introduces the idea of a "purpose" for the universe and opens up scientists to the question of the true nature of their very desire to know.

Paul Davies[40]

The mystery that now confronts us is this. How did human beings acquire their extraordinary ability to crack the cosmic code, to solve nature's cryptic crossword, to do science so effectively? I have mentioned that science emerged from a predominately Christian culture. According to the Christian tradition God is a rational being who made the universe as a free act of special creation, and has ordered it in a way that reflects his/her own rationality. Human beings are said to be "made in God's image," and might therefore be considered (on one interpretation of "image") to share, albeit in grossly diminished form, some aspect of God's own rationality. If one subscribes to this point of view it is then no surprise that we can do science, because in so doing we are exercising a form of rationality that finds a common basis in the Architect of the very natural world that we are exploring.

Should this be called teleology? Certainly the universe develops as if it is being directed towards a specific end state, but in fact its future development is to a large measure open, so that the impression of detailed directedness can be illusory. On the other hand, we are not faced with cosmic anarchy. There is a general tendency towards stability, organizational complexity, increasing variety, and so on. These trends are a consequence of the lawfulness of nature. We are thus led to a more subtle notion of "design," in which a judicious selection of laws bestows upon the universe the potential to create richness and complexity spontaneously, but the inherent openness precludes detailed "fixing in advance."

The use of the word "design" could be questioned here. One problem involves the implication of temporality. It is important to realize that time is itself part of the lawful fabric of the universe, and the laws to which I refer have a timeless, eternal character. Therefore it is misleading to think of the laws as devised in advance, in the temporal sense. They should be regarded as logically, rather than temporally, prior. Possibly a better word to use is "purpose." I contend that the laws of nature are such as to facilitate the evolution of the universe in a purposelike fashion. Again, it is often objected that purpose is a concept that can be applied to human beings, and possibly other organisms or minds, but not to a universe. In response I would say that it is not necessary to imbue the universe with humanlike purpose as such for it still to exhibit purposelike behavior.

We want to know why the laws of nature are what they are, and in particular why they are so ingenious and felicitous that they enable matter and energy to self-organize in the unexpectedly remarkable way I have described, a way suggestive of design or purpose (in some suitably modified sense). To me, it points to a deeper level of explanation than just accepting the laws as a brute fact. Whether this deeper level can legitimately be called God is for others to decide.

Purpose 7

There are five stimuli which can incite man to science. There are men who want to know simply for the sake of knowing: this is common curiosity. Others seek to know so as to be known: this is pure vanity. Others want to possess science to be able to sell and gain money and honors: their motive is meanness. But some desire to know in order to educate, and this is charity; others to be educated, and this is wisdom. **ST. BERNARD**

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

T. S. ELIOT[1]

ASK A SCIENTIST what is the aim of his or her work, or what is the goal of the scientific undertaking, and you may find elusive and perhaps somewhat embarrassed answers. Some scientists could even refuse to reply, calling the question illusory or a waste of time. But basically they will have the same reaction to questions as one expects from a manager of industry or a teacher at an elementary school. We live in a cultural context in which it is not customary to ask ourselves why we are doing something. Clearly the question about the purpose of science is not one that can be approached with the scientific method; it does not call for the solution to a problem in chemistry or physics, but for the observation of the human phenomenon of doing research, the "existential" action of the researcher.

To what end? A first motivation can come from the usefulness to human society of the achievements of science. Beyond doubt the progress of science improves, or can improve, the conditions of human life. Biology and medicine have allowed us to fight against devastating diseases; technology, mainly derived from physics and chemistry, spares us hard labor that previous generations had to endure, though with all the risks and counterindications that we know well. It may sound as just a commonplace, but in fact it is difficult to underestimate how deep the impact of scientific discoveries has been on human society, on the way in which we live, on our expectations for the future. But it is interesting to observe that the majority of technological advances, now necessary for survival in contemporary societies (try to live in Helsinki without electricity or in Denver without an automobile!) have been made under the thrust of motivations that have little or nothing to do with the applications that have followed them. When Maxwell studied electromagnetism he certainly did not imagine what profound and great practical consequences his researches would some day have. He investigated with great curiosity—we could almost say "played" with—elusive, subtle, apparently insignificant phenomena remote from the experience of most people. Unlike the force of gravity, in fact, electrical and magnetic forces, though they are everywhere, are not readily perceptible to our senses. But it was only an understanding of the laws of nature that govern electromagnetism that opened the way to a great variety of applications, ending up by profoundly changing our way of living. Every time we turn on the light, every time we listen to music on the radio, every time we work with a computer, we are in some way using the consequences of the work of scientists at grips with their insatiable curiosity. If rather than leaving Maxwell in the uncertain garden of his equations and experiments one had asked him to design an alternative system for communicating over distances or lighting the streets, he would probably never have discovered his splendid system of fundamental laws, and perhaps we would not even have had record players and street lamps (at least until another boy scientist had entered the game park).

The aim that researchers have normally precedes and dominates the desire to produce socially useful applications. The aim pursued in research for which scientists often show an almost monastic dedication probably has its roots in a more hidden level of the person involved. It goes with that silent and powerful attraction that alerts scientists to the characteristics of order, beauty, variety, and unity in the natural world that they seek to investigate—an attraction that is not necessarily theorized or asserted in an explicit way. In previous chapters we have noted that natural reality appears to scientific investigation to be organized according to a "given" order, an order not imposed by external schemes, that reveals itself through laws and regularities—an order that mysteriously corresponds to the capacity of human reason to understand beyond any reasonable aspect. Moreover, this order does not appear to be "the only order possible" but "a certain very precise order" that has led the universe to be an environment suitable to be inhabited by life, a "terrain" finally capable of accepting that irreducible and vertiginous reality that is the human person. The more science leads us to observe nature at close quarters, the more we note that our existence requires the support and collaboration of all the natural world, from the fundamental laws of physics to the particularities of terrestrial geology. Wise country folk know that their lives depend on the providential changing of the seasons and the generosity of the earth; today scientific knowledge confirms and extends the evidence of the profound dependence of our existence not only on immediate circumstances that we encounter directly but also on the distant periphery of the universe, down to the details of microscopic and macroscopic structures.

The universe appears as a fresco in which order, beauty, and direction are like different but inseparable colors. If the nature of its interior indicates an order and suggests a direction, then the task to which the scientist is called will be that of attempting to bring to light the links between things (the laws) on which such order is based and to track down the signs of his destination. Behind various appearances every scientist cherishes the hope of being able to contribute in some way to shedding light on an aspect, whether small or large, of the great fresco. This is his or her secret, and it exercises an irresistible attraction that multiplies one's enthusiasm and energy. Erwin Schrödinger argued that the objective, the goal, and the value of the natural sciences is the same as any other branch of human knowledge. The contribution of science is added to that of the other human ways of becoming aware of oneself and of reality. Just like music, literature, and art, science too expresses the deep human desire for truth.

In this sense scientific knowledge, far from having a self-defined value and being enclosed in itself, is an instrument, a point of view, a "chance" granted to human beings to give voice and space to the questions that move and constitute them. Schrödinger also asserted that "the question that nags us is where we come from and where we are going." The inextinguishable question that supports and gives energy to human activity and to every attempt to know relates to the meaning of our being and that of things, their origin and destiny.

Science certainly does not have either the capacity or the right to give an answer to ultimate questions, and when it claims to do so, it becomes violence and ideology. Rather, science can contribute to making the question of meaning concrete, fascinating, powerful, and dramatic, and it does so by approaching reality from the narrow but clear perspective of its method, offering a partial but suggestive view on reality that cannot be obtained with any other method of knowledge.

"Of what things and through what things is reality made?" The impetus of these questions works as a hidden engine in the efforts of the individual scientist as in the dissemination of the scientific enterprise as a whole. From this perspective, from within their activity, scientists are "in fact" immersed in the religious level, if this is understood not as a particular faith in which they believe or do not believe, or a totality of moral laws that they follow or do not follow, but as that fundamental level of reason that is the need for an exhaustive meaning of reality.[2]

And when a scientist has the gift of faith, when with great emotion his reason recognizes the presence of the Creator in the sign of the creature, then the picture becomes more simple. The certainty that every visible or invisible creature has been and is willed by a good arouses curiosity, and increases humility and the desire to follow the signs of things as they present themselves. For the researcher who has faith in the Lord of heaven and earth, the taste for discovery coincides with the possibility of discovering a feature of the world that he has prepared for us.

Purpose and Responsibility: This Scientist, So Powerful yet So Impotent

The usefulness of the results of scientific knowledge is part of the dynamic of the scientific enterprise, even if it certainly does not exhaust it. The capacity of human beings to utilize science for the human good first of all requires the recognition that all reality, including ourselves, is a gift that we receive—not a product of our imagination or brilliance—and is admired and used as such.

Vannevar Bush, the founder of the National Science Foundation, suggests an effective image for describing the process of science in which its application also has a place.

Vannevar Bush[3]

The process by which the boundaries of knowledge are advanced, and the structure of organized science is built, is a complex process indeed. It corresponds fairly well with the exploitation of a difficult quarry for its building materials and the fitting of these into an edifice; but there are very significant differences. First, the material itself is exceedingly varied, hidden and overlaid with relatively worthless rubble. . . . Second, the whole effort is highly unorganized. There are no direct orders from architect or quarrymaster. Individuals and small bands proceed about their business unimpeded and uncontrolled, digging where they will, working over their material, and tucking it into place in the edifice.

Finally, the edifice itself has a remarkable property, for its form is predestined by the laws of logic and the nature of human reasoning. It is almost as though it had once existed, and its building blocks had then been scattered, hidden, and buried, each with its unique form retained so that it would fit only its own peculiar position, and with the concomitant limitation that the blocks cannot be found or recognized until the building of the structure has progressed to the point where their position and form reveal themselves to the discerning eye of the talented worker in the quarry. Parts of the edifice are being used while construction proceeds, by reason of the applications of science, but other parts are merely admired for their beauty and symmetry, and their possible utility is not in question.

If it is true that the building has a design that is not ours, the question remains for us "if," "when," and "how" we are to utilize some of its rooms, which to use, and for what end. Science does not itself define the purpose for which it exists, nor is it in a position to deduce from within itself the direction in which to make possible applications. The perspective of the social utility of technological applications determines at least in part the financial support and therefore the strategic orientation of scientific research: the links between science and technology are deeper than one might think.

Victor F. Weisskopf[4]

Very rarely are scientific discoveries made with a specific purpose in mind to which they are going to be applied. Faraday did not think of the motor when he studied the relations of electricity and magnetism. Hertz did not think of communication when he discovered radio waves, and certainly, Curie, Rutherford, and Chadwick did not contemplate nuclear energy or cancer treatment when they worked on radioactivity. After the famous lecture on electricity given by Faraday to the Royal Society, a British Member of Parliament asked: "What is the use of all your beautiful experiments?" and Faraday replied: "What use is a newborn baby?" The baby grew up to be the electrical industry.

Today, technology and science depend completely upon each other; they are in a symbiotic relationship. Technology cannot advance without science, nor science without technology.

Here is a brief outline of this symbiosis. Considering only the physical sciences, three great scientific discoveries were made during the nineteenth century: the existence of atoms and molecules, the nature of heat as a disordered motion of atoms, and the unity of electricity, magnetism, and optics. The theory of heat evolved from the steam engine; the development of electromagnetism and optics led to the electrical, optical, and communications industries; and, of course, the recognition of atoms and molecules brought the chemical industry into existence.

The twentieth century witnessed, in its first quarter, an ever growing insight into the structure of the atom by means of quantum mechanics. In parallel we saw the development of electronic industries based upon a better understanding of the interactions between electrons and atoms. When the nature of the chemical bond was revealed by further applications of quantum mechanics to atomic and molecular dynamics, a deeper understanding of the structure of metals, crystals, and other materials was achieved. This led to an expansion of chemical industries and to the production of new materials. It finally brought about the invention of transistors and semiconductors on which the computer industry thrives.

The next scientific step into the deeper layers of matter was the penetration into the structure of the atomic nucleus. Nuclear physics has brought about the exploration of nuclear power and the applications of artificial radioactivity to medical purposes and materials testing. Biology, with its revelations of the chemical nature of the life process, has found many fruitful applications in medicine and in the chemical industry.

On the other hand, none of these scientific steps could have been taken without the help of technology. This is most obvious in more recent developments that would have been impossible without the help of the latest achievements of electronics and other precision technology. . . . [I remind you of the complicated and sophisticated technology that goes into the construction of a modern accelerator.]

This tremendous development was much wider and greater than ever expected. It underwent an exponential growth that we still witness in the recent development of computers and lasers. The astounding success of science and technology had a deep influence on the entire social fabric. Our society, our philosophy, and our thinking have been shaken to the core.

Today the enormous potential of technology puts our responsibility in question in a formidable way. In one of his most famous remarks, Einstein warned, "A preoccupation with man and his destiny must always be the main interest of all technical efforts; never forget that in the midst of your diagrams and all your equations."

Among the voices repeatedly raised to indicate to all the urgency of taking responsibility, that of the Catholic Church stands out. It is always particularly attentive to this problem, whether in endorsing the positive potential of technology[5] or in warning against the enormous risks that it brings, passionately affirming the irreducibility of the human person, the inestimable value of the individual. In 1980 John Paul II asserted to a group of Nobel Prize winners: "This, gentlemen, is the decisive criterion: the criterion of serving man, the whole man, in the whole of his spiritual and bodily subjectivity."[6]

To give an idea of how relevant and disenchanted is the emphasis in the pope's request in reaffirming such a criterion, we offer this rather disturbing passage from an address by Lowell L. Wood, who describes the radical challenge that potential future developments of microelectronics and molecular biology might pose to the very identity of the human being.

Lowell L. Wood[7]

It now seems that the rapid pace assumed by technological progress could very soon pose fundamental choices to humanity in the third millennium. For at least on two axes—microelectronics and molecular biology—we face the prospect of a profound change in the human condition during the first half of the twenty-first century.

. . . Purely quantitative extensions of current tendencies make it very clear that in the next decades the majority of the human race will tacitly choose to be something rather different from an aggregation of concentric circles of autonomous individuals, in an extended family, in a community, in a culture that has constituted the foundation of the Western model of humanity for many centuries. . . . The probable advance of technological progress during the next twenty-five years will be such that at least the elites of telecommunications will be able, by 2020, not only to share a large set of digital data but also many of the most lively aspects of life as experienced in quasi-real time. How such a sharing, down to broadband and zero latency, of all that we see and feel can change the human condition and human experience is not completely clear in the current perspective, but it is clear that the change will probably be deeper than the global impact on human culture of all the communication technologies so far introduced. A large part of the characteristics—and the traditional narrow-mindedness and autonomy of the individual—of a significant fraction of the human species can therefore converge, mix, probably in an irreversible way, in something that recalls "group awareness."

. . . Those of you who have a personal computer can change your personal programs and your databases every day, add or update your package of programs every month or every three months, but probably change the hardware every two or three years. It seems quite probable that people are beginning to consider their own genomes in a very similar way in the first century of the third millennium. Genetic surgery is already offering to some people like us, affected by congenital diseases, the opportunity to replace critical components of their genetic endowment that are malfunctioning with some that are more normal.

. . . It seems probable that a mass market for improving the human somatic genome by mouth or by injection will arise in the first century of the third millennium, far and away exceeding the mass demand and the economic incidence of the current demand for software for personal computers, to which it is very similar in many aspects. Genetic improvements for the imperfect aspects of the structure and functioning of our bodies will be put on the market, publicized in the media of the "global village" and sold first to millions, then to hundreds of millions, and finally to billions of customers who want to obtain them. There will be a great competition between gene banks which attract attention and the stock exchange of the bigger and more interesting mass market of history. Economies of scale will form that will allow the most efficient sellers to make offers . . . at prices that will make them accessible everywhere to all human beings except the very poorest.

. . . Market incentives, already a powerful stimulus to the progress of molecular biology, will provide an impetus during the next decades such that the microelectronic revolution of the past twenty-five years will seem a slow minuet. The way in which human beings think of the human will necessarily be greatly changed by the advent of a human life without adventures and with a potential of incredibly great length.

. . . Whereas the prospects for the genetic restructuring of the human germ cell tend to be considered with some prudence by the few who are not currently engaged in it, it seems probable that it will not only be tolerated but requested as soon as the somatic genetic restructuring of human beings shows its value during the next fifty years and people decide to make permanent in the genetic patrimony of their descendants the genetic progress that they have personally experienced and valued. This process will probably begin with the creation of different races of *Homo sapiens posthomo* and continue with the synthesis of new species of *Homo*, forms of life similar to human beings, whose genomes have progressed in such a way that they can no longer be combined meiotically with those of today's human beings. At some point in this process attempts to bring about recombinations will be banned, just as today proposals to try to cross human beings with chimpanzees in experiments are banned.

In the course of the twenty-first century "bestiality" could assume a new meaning and, after an interval of a few generations, the remaining representatives of *Homo sapiens* could be found on earth "only" as the last acquisitions of the great zoo. ✺

This horrifying vision of our future is probably unrealistic and hopefully will remain only a good subject of science fiction movies. But it is not pure fantasy. The danger comes above all from a widespread phenomenon that we can observe today: together with the explosion of a sense of power deriving from the achievements of science, our mentality is showing a progressive "decay of a sense of meaning."

Victor F. Weisskopf[8]

Great insight leads to great power; great power always leads to great abuse.

The decay of a sense of meaning and the increase of cynicism in our culture have also contaminated natural scientists. These trends have shaken the conviction of some members of that community, but there is still a good deal of belief in the purpose and meaning of their collective work. I cannot help feeling that they represent a "happy breed of men" among so many others who grapple with the problems of meaning, sense, and purpose.

As if in response to the tragic scenario depicted by Lowell Wood, the geneticist Jérôme Lejeune, a convinced supporter of the benefits that science can bring for the improvement of human life, denounces the situation of twenty-first-century human beings and sounds the alarm for the "increasingly disturbing lack of equilibrium" between "their power, which is increasing, and their wisdom, which is declining."

Jérôme Lejeune[9]

Human intervention in the manifestations of life has increased notably in the recent past, in all its possibilities. From the Paleolithic age to our days, with the domestication of animals and the selection of useful plants, human beings have made genetic manipulations in natural phenomena.

It is only very recently that a greater knowledge of the modes of the transmission of life has broken this equilibrium with the introduction of techniques that the natural processes could not implement in any way. To give just one example, the use on a large scale of artificial insemination on breeding animals has made it possible to overcome otherwise insurmountable geographical barriers and barriers of sexual behavior. Thus, the genetic manipulation of bacteria has recently made it possible to modify some genetic characteristics at will and to create matrices that no natural or artificial selection has ever been able to produce.

Such an explosive increase in our knowledge can become a formidable danger, so that genetic manipulations now seem also to be applicable to human beings.

This brutal break in an equilibrium that has lasted for millennia, between the thinking being and living nature, generates profound anxiety. Does our generation possess sufficient wisdom to use a denatured biology with prudence?

. . . The dawn of science is on the point of totally rediscovering humanity, and we must prevent it from becoming suffocating. This dawn is producing good fruits and bad fruits. We are forced to choose. It is necessary for modern society to begin to understand that science in itself is neither useful nor pernicious, but that it can become one or the other depending on whether it is used to serve human beings or degrade them.

The manipulations of which I have spoken are not just a danger for the future if we consider the whole planet. But the real danger lies in human beings, in the increasingly disturbing lack of equilibrium between their power, which is increasing, and their wisdom, which is declining. It is wise to be a good apprentice, and the duty of every scientist, but it is foolish to play the wizard; no one can ever become one. Beyond intelligence there is another law of life that also dominates reason. It is love of one's like, defense of the weak, compassion for those who suffer, and unlimited respect even for those who are distant, alien, different, and for those unknown who will survive us on this earth.

According to Lejeune, respect for and defense of "one's like" constitutes a fundamental criterion for the scientist. On the other hand, history has often shown how fragile is the capacity of human beings to use with wisdom the enormous power that science has put in their hands. After the ruinous experience of the application of nuclear energy in war with the atomic bombs dropped on Hiroshima and Nagasaki on August 6 and 9, 1945, which caused 145,000 deaths, Albert Einstein declared bitterly that if he were born again he would do some other work, not physics. In a passage from the hearing to which Oppenheimer was subjected, narrated in Robert Jungk's famous novel, the drama of the scientists who took part in the construction of the first atomic bomb, who can become the symbol of all scientists, emerges: the awareness of having too powerful an instrument in hands that are too fragile.

J. Robert Oppenheimer[10]

On 22 April 1954 Robert Oppenheimer achieved the age of fifty. In normal circumstances the day would have been one of rejoicing for so successful a man. But as it happened this was a day of judgment. It fell in the second week of the proceedings, during the long procession of witnesses. All who had hitherto spoken had been full of praise for Oppenheimer. They had commended his energy and the qualities of leadership he had shown as Director at Los Alamos, his realization of the need for strict measures against espionage, his organizing capabilities and his loyalty.

But before each witness, often after hours of examination by Gray, Robb and

Oppenheimer's counsel, came to the end of his evidence, Professor Evans usually cut in to put a question about the personal characters and habits of the scientists who testified. He did so on this particular morning.

Norris Bradbury, Oppenheimer's successor as Director at Los Alamos, was seated on the leather couch. Evans addressed him in the following terms:

Dr. Evans: Do you think that scientific men as a rule are rather peculiar individuals?

Bradbury: When did I stop beating my wife?

Mr. Gray: Especially chemistry professors?

Dr. Evans: No, physics professors.

Bradbury: Scientists are human beings. . . . A scientist wants to know. He wants to know correctly and truthfully and precisely. . . . Therefore I think you are likely to find among people who have imaginative minds in the scientific field individuals who are also willing, eager, to look at a number of other fields with the same type of interest, willingness to examine, to be convinced and without a priori convictions as to the rightness or wrongness, that this constant or this or that curve or this or that function is fatal.

I think the same sort of willingness to explore other areas of human activity is probably characteristic. If this makes them peculiar I think it is probably a desirable peculiarity.

Dr. Evans: You didn't do that, did you?

Bradbury: Well—

Dr. Evans: Do you go fishing and things like that?

Bradbury: Yes, I have done a number of things. Some people and perhaps myself among them, I was an experimental physicist during those days, and I was very much preoccupied by the results of my own investigations.

Dr. Evans: But that didn't make you peculiar, did it?

Bradbury: This I would have to leave to others to say.

Dr. Evans: Younger people sometimes make mistakes, don't they?

Bradbury: I think this is part of people's growing up.

Dr. Evans: Do you think Dr. Oppenheimer made any mistakes?

Thus the main subject of debate, Robert Oppenheimer, had again cropped up.

. . . This statement and very many others made between 12 April and 6 May 1954 in Room 2022 contributed not only to the life-story of a single man but also to that of a whole generation of atomic scientists. The evidence revealed their untroubled youth, their dread of the dictators, how they were dazzled by the overwhelming nature of their discoveries, the heavy responsibility for which they had not been prepared, the fame which threatened to be their ruin, their inextricable involvement and their deep distress. It was not only Robert Oppenheimer's fate which was being discussed in that narrow courtroom. The debate concerned all the new, unsolved problems with which the onset of the atomic age had confronted scientists. It concerned the new part they had to play in society, their uneasiness in a world of mechanized terror and counter-terror which they themselves had helped to create, above all their loss of that deeply rooted set of ethical beliefs out of which all science had formerly grown.

To study the statements made by these outstanding minds at this hearing, statements about themselves and their fate which at the time they never dreamed would be laid before a wider public, is to ask oneself why such first-rate calculators found such an entirely unexpected answer to the calculations they made in practical affairs. Why was it they in particular who had been drawn into the storm-centre of politics, when they had after all taken up their calling in the first place mainly because they wished to turn their backs upon a chaotic and lawless world? How had it happened that people who had embarked upon their careers in order to ascertain a more comprehensive truth were in the end obliged to spend the best years of their lives in the search for more and more comprehensive means of destruction? . . .

The questions put by Dr. Evans during these proceedings were quite often supposed to be of minor interest and off the main point of the "Oppenheimer case." But in reality it was these very queries which were aimed, for all their assumed naivety, at the very heart of the biggest problem of all, which Oppenheimer's fall had thrown into relief. What was the true character of this new figure, the scientist, so powerful and yet so powerless?

This unconventional chemistry professor, invariably humane even when acting as a member of an official investigation committee, probably spoke for all those ordinary citizens who, he may have felt, regarded him with a mixture of admiration and fear since they had ceased to consider his profession as comic and now looked upon it as something terrible. "Are scientists peculiar people?" The crude queries of this sort, put by Evans, were in reality echoes of the voices of millions of anxious persons who would have liked the men of science to answer such questions as: "Are you the same sort of beings as we are? Do you still see any sense in moderation, in the dignity of man and the commands of his Creator? Won't you tell us what you are really after?"

The atomic scientists who gave evidence in turn before the Personnel Security Board were themselves, in fact, also in the dock. And the critical question on which they ought to have given their views was not "Have you been loyal to the State?" but "Have you been loyal to mankind?"

Almost all scientists would agree in asserting that science must be developed for the common good. But how is it possible to maintain such a position? What could help to sustain a just and reasonable use of our growing dominion over nature? To answer these questions, which are dramatically urgent, it is not first of all within science that we should look for an answer. Scientific knowledge does not itself offer the criteria for being put to human advantage, or for avoiding the disastrous consequences of which it is potentially capable. The danger comes from a kind of myopia that afflicts modern human beings, so that the fact that "something works" seems sufficient to say that "it's good." We must guard against this "idolatry of the instrument. It is true that the instrument multiplies human efficiency beyond all limits; but is this efficiency always to their advantage? Does it make them better? More morally sound?"[11]

It is important to look at the whole reality of the human being, at our being constituted by the relationship with the Mystery that makes it and for which every human being is made. The Catholic Church, witness to an unprecedented conception of the human person,[12] has always defended and proclaimed the immeasurable value of the individual: "Technical science, aimed at the transformation of the world, is justified on the basis of the service it renders man and humanity."[13] A science unleashed from the tension of the "entire good" of human beings can conquer the whole universe with knowledge but will fatally lead to humiliation of the human person and become an instrument of power: "What does it profit a man if he gains the whole world, but loses himself?"[14]

In an interesting theatrical presentation of Galileo's recantation, written by the astrophysicist Nicolò Dallaporta (explicitly without any claim to historical interpretation), the problem of the separation of science from truth as a whole is taken back to its initial moment. Galileo, in dialogue with his pupil Remo Sandrelli and the publisher Malvasi, has a sense of the negative consequences of his science "beautiful and pure, which brings forth a monster," a science which, "detached from faith, gives a start to its crazy course"; this is why he decides to recant.

Galileo Galilei–Nicolò Dallaporta[15]

[Sandrelli has just outlined the possible developments of a science that becomes an instrument for dominating the world and enslaving human beings; Galileo, upset, continues the dialogue with Malvasi.]

Malvasi: Well? Do you see?

Galileo (stopping and looking at Sandrelli): To my eyes, while you were speaking, Remo, the panorama of the new world in the making was unfolding: a vast carpet of machines, increasingly different and perfect, with servants around to clean them and feed them. All in a series, planned. . . . No potter, no carpenter, no smith could create an object in which a simple touch produced thousands of vases, chairs, lamps, all prefabricated and the same. . . .

Malvasi (continuing): Mountains of goods . . . and among these also arms, increasingly deadly and sophisticated.

Galileo: Everything provided by ever greater complexes in which the heirs of man will repeat the same actions from morning to night. And when their work is done, like bees which swarm, they will throng by some autonomous means of transport to equal cells, in equal hives, in the vain quest for a happiness which escapes them because, having leveled everything down, they will have suffocated the very divine imprint in them! . . .

Malvasi (cautious and indecisive): And will it be possible to warn against this?

Galileo (with alarm): I must recognize with sorrow that this world of Sandrelli's is not just the nightmare of a madman, but the logical consequence of science, and a practical end.

Malvasi (with a sign of relief): At last you've understood!

Galileo (coming near to him with warmth): But tell me. How can science, which is beautiful and pure, give birth to such a monster?

Malvasi (softly): If it detaches itself from faith, it gives a start to its crazy course.

Galileo (in torment): But isn't science also a light in the quest for God?

Malvasi: It will be that only in the hands of angels. . . .

Galileo: And not in the hands of man? (realizing, anxious) For the sin of our race?

Malvasi (casually): If as an experimental physicist I am right, it will prove that original sin does not seem to be such a stupid story: it presents an empirical fact, the contrast between the spiritual heights to which the human mind ascends and its incapacity to put them into practice.

Galileo: So doesn't man support himself? Left in anyone's hands, could science perhaps be degraded into an instrument of use, of power? Who cares what you call it . . . metaphysics?

Malvasi: Without a metaphysic, man does not rule. . . . And anyone who attempted one day to abrogate it would necessarily raise science to such a status, by dogmatizing the axioms. . . . And those who attempt to exploit it for commercial ends would gain the upper hand.

Galileo (sadly): That's why pearls are never given to swine!

Malvasi: Present-day authorities, in that they exalt themselves, do not care to look after pearls. . . . But then it is necessary to condemn the decadence of such authorities, not its principle. . . . We mustn't commit the usual error: when something deviates from its proper course, men stigmatize the institution, even repudiate the action. . . .

Galileo (after reflection, morosely): And from so much, whatever derives?

Malvasi: Sandrelli's world arouses us against faith in lethargy. . . . For him the life which burst out irresistibly is necessarily joined with what itself proves to be partial, and therefore error. . . . In the paradoxical drama of our time life and truth are disjunct, in antithetical positions.

Galileo: And will that last?

Malvasi: Until we know how to reconnect truth with life, in a way which keeps the two together.

Galileo: Today science, which lives, devours faith, which sleeps. So which is the way to follow?

Malvasi: To the point where, with such immature human beings, science can be kept under control. . . . Sandrelli's world is at the gates; we are expected to delay its coming.

Galileo (with difficulty): In view of the way that reconnects life with the truth? (morosely) But this is an indeterminable truth in the face of a concrete threat, something that doesn't leave much margin for recovery. . . .

Malvasi: Often, to save the world, no more than a twig is offered. . . .

Galileo: And do you think that I am the one who must throw the first twig? (pause) And in what way?

Malvasi: You know very well. . . .

Galileo (bitterly): By recanting? For such a tenuous thread of hope?

Malvasi: If you refuse to recant, and move toward martyrdom, you will become a standard which gives the victory to error.

Galileo: And if I recant?

Malvasi: Make a truce with those authorities which, degraded though they may be, compared with Sandrelli's world seem at any rate to be a residue of light because they support those hidden values which motivate every possible way of reintegrating faith with life.

Galileo (tensely): So with this recantation must I perform the obsequies over the petrifaction of the truth?

Malvasi: This is the supreme paradox: in order to keep open a way to an uncertain tomorrow in which, who knows when, life and truth can perhaps be reunited, you must deny the purpose of your life and the partial truth of science, to pay homage to authorities which would not deserve a way out, did not their defeat prepare for the triumph of what would be far worse than them. . . . This is what God requires: do you feel that you can obey such a hard order?

Galileo (morosely, and after a long hesitation): I will recant! . . .

Sandrelli: Do you accept? . . .

Galileo: In spite of all false motives that they will attribute to my gesture: cowardice, ignorance, compromise.

Malvasi (softly): God alone sees the meaning. . . .

Galileo (with alarm): I will recant to slow down the degradation of the world which threatens, and which kills my hope. . . .

Malvasi : Even Christ despaired in his supreme hour. . . .

Galileo: In the end I will abjure for that very slender light in which the Truth is united with life and which perhaps will never be lit (shaking his head). Moreover no one is asking me. How, after I have dug with my hands the graves of my progeny, could I do otherwise, I an experimenter, I a physicist, than turn to this my mutilated science, nevertheless infinitely loved by me?

Malvasi: To a purified science, in a hermitage, in silence, near to your daughter, whose intention welcomes you in this way. . . . This is the way for you to follow, which will form the right conclusion to your life.

(After a brief pause) I don't think that we need say anything else, and with these words I will take my leave. I have nothing else to do in this place.

Purpose and Harmony: The Sound of the Ancient Music of the Spheres Returns

The possibility of socially useful applications does not exhaust the motivation of researchers. Why do they do what they set out to do? They aim to discover the order with which reality is formed. As we saw in the previous chapter, this is a particular order. The laws of physics have accompanied the whole history of the universe and have allowed or favored or determined incredible fruits. This is not a static order or an aim in itself but is capable of developing complexity and variety.

The fact that reality is characterized by a harmony, by an order aimed at a goal, is relevant for understanding the profound motivations that lead people to science.

Hubert Reeves[16]

After the question, "Why something rather than nothing?" we are now led to ask, "Why music rather than noise?"

When I speak of "music," I am speaking metaphorically. It is a generalized sense of music that I mean, a bit like the ancient idea of the "music of the spheres," not limited to celestial bodies, but now including atoms and molecules as well. It is anything that manifests the magnificent orderliness of our cosmos. In order to write music (in the literal sense of the word), the composer chooses a certain number of elementary tones. He places them in a particular sequence that will unfold with time. If these tones have been chosen randomly, and if there is no relation between a tone and the ones that precede and follow it, we have "noise." If they are ordered according to a particular structure, whether that of J. S. Bach or that of the Beatles, we have music. There is an infinite number of ways to make noise, but a much more limited number of ways to make music.

The fact that natural reality presents itself with an order and a direction suggests that the underlying aim of the scientist is defined by his or her desire to unveil the secrets of such order with the means and from the perspective typical of the scientific method. Several scientists have spoken out openly on this. For Einstein the motivation lies in the desire to put the various apparently disordered varieties of experience in a unitary picture, in order to bring to light a profound order underlying appearances.

Paul Davies[17]

How does it happen that the laws of the universe are such as to favor the emergence of minds which in their turn are capable of reflecting and modeling themselves accurately on those same mathematical laws? How has it come about that the human brain, which is the most complex and developed physical system that we know, has produced among its most advanced functions something like mathematics, capable of explaining with such success the most basic systems of physical reality? Why does the mind, which is at the height of the development, fall back on itself and connect with the basic level of existence, that is, with the order of laws on which the universe is built? In my view this strange loop suggests that the mind is bound up with the most fundamental aspects of physical reality, so that if there is a meaning or a purpose of physical existence, we conscious beings are certainly a profound part of this purpose.

Albert Einstein[18]

Science is the attempt to make the chaotic diversity of our sense-experience correspond to a logically uniform system of thought. . . . There has always been present the attempt to find a unifying theoretical basis for all these single sciences, consisting of a minimum of concepts and fundamental relationships, from which all the concepts and relationships of the single disciplines might be derived by logical process. This is what we mean by the search for a foundation of the whole of physics. The confident belief that this ultimate goal may be reached is the chief source of the passionate devotion which has always animated the researcher. . . .

The harmony that scientists indicate is not the fruit of their intervention into things; it is not like a child sorting out its toys in a room or a shopkeeper compiling a list of goods. Rather, it is a profound order inherent in objective reality. The correspondence between the intrinsic order of the universe and the capacity of human reason lies at the origin of the mystery of the comprehensibility of the world (see chap. 5). In this fragment of a letter from Einstein to Maurice Solovine, all the enthusiasm for the evidence of a "high degree of ordering of the objective world" comes through. In an analogous way Max Planck identifies in the coincidence between human thought and the manifestations of the natural world the origin of the commitment and "the most sublime scientific pursuit."

Albert Einstein[19]

You find it strange that I consider the comprehensibility of the world (to the extent that we are authorized to speak of such a comprehensibility) as a miracle or as an eternal mystery. Well, *a priori* one should expect a chaotic world which cannot be grasped by the mind in any way. One could (yes one should) expect the world to be subjected to law only to the extent that we order it through our intelligence. Ordering of this kind would be like the alphabetical ordering of the words of language. By contrast, the kind of order created by Newton's theory of gravitation, for instance, is wholly different. Even if the axioms of the theory are proposed by man, the success of such a project presupposes a high degree of ordering of the object world, and this could not be expected *a priori.* That is the "miracle" which is being constantly reinforced as our knowledge expands.

There lies the weakness of positivists and professional atheists who are elated because they feel that they have not only successfully rid the world of gods but "bared the miracles." Oddly enough, we must be satisfied to acknowledge the "miracle" without there being any legitimate way for us to approach it. I am forced to add that just to keep you from thinking that—weakened by age—I have fallen prey to the parsons.

Max Planck[20]

My original decision to devote myself to science was a direct result of the discovery which has never ceased to fill me with enthusiasm since my early youth—the comprehension of the far from obvious fact that the laws of human reasoning coincide with the laws governing the sequences of the impressions we receive from the world about us; that, therefore, pure reasoning can enable man to gain an insight into the mechanism of the latter. In this connection, it is of paramount importance that the outside world is something independent from man, something absolute, and the quest for the laws which apply to this absolute appeared to me as the most sublime scientific pursuit in life.

Charles Eugène Guye[21]

If on the one hand we accept that our universe, and in particular human destiny, has a purpose, and if, on the other hand, we have to some degree the possibility of contributing individually to its realization, then there appears a necessary reason which reveals itself at the same time as one of the essential conditions for perfection and progress and one of the joys of life. How could we admit, in fact, that whereas such an important part has been made in the human brain for intelligence and for emotional qualities, there is nothing in this world to understand and to love; and that the exercise of what we rightly call the highest gifts of the mind and the heart are without purpose and without any effect on our individual destiny or, at least, on that complex evolution of human destiny with which we seem to be in solidarity? ✺

On the occasion of Max Planck's sixtieth birthday, Einstein made an observation that expresses the scientist's position in an admirable and succinct way: his indomitable action is motivated not so much by a project or by force of will but by the longing to contemplate "preestablished harmony."

Albert Einstein–Max Planck[22]

The longing to behold . . . preestablished harmony is the source of the inexhaustible persistence and patience with which we see Planck devoting himself to the most general problems of our science without letting himself be deflected by goals which are more profitable and easier to achieve. I have often heard that colleagues would like to attribute this attitude to exceptional willpower and discipline; I believe entirely wrongly so. The emotional state which enables such achievements is similar to that of the religious person or the person in love; the daily pursuit does not originate from a design or program but from a direct need. ✺

Can one speak of a purpose for mathematics? According to Safarevič, its harmony and its internal solidity indicate that the answer must be affirmative. This purpose is not sought in an "inferior" activity, such as that of its possible practical applications, but at a superior level: the relationship with mystery, the "religious" level.

Igor R. Safarevič[23]

Every being is inclined to accept its own environment as something absolute, something that cannot exist otherwise and that therefore raises questions. Even mathematicians see their own science in this way and only rarely—when they have occasion to consider it from outside—realize that they are occupied throughout life with a strange and substantially improbable phenomenon. This occasion was presented to me when I had the honor of being invited to say a few words about mathematics to scientific colleagues who were working in sectors outside mathematics.

Mathematics, seen superficially, appears to be the fruit of the labors of thousands and thousands of individuals with little connection between them, spread over various continents, over centuries and millennia. However, the internal logic of its development recalls rather the labor of a unique intellect that incessantly and systematically develops its own work by using the multiformity of the individuals involved uniquely as an instrument. It is like an orchestra that performs a symphony in which the theme passes from one instrument to another and in which, when a player has to interrupt his own part, another picks it up with exactly the same note.

This, believe me, is not a rhetorical figure. The history of mathematics knows many examples of discoveries made by a scientist which remain unknown, then to be reproduced with surprising precision by another. Galois, in a letter written the night preceding the duel which was to cost him his life, made some extremely important observations on the integrals of algebraic functions; more than twenty years later Riemann, who could not have known of this letter, discovered the same theses again and demonstrated them with precision.

After Lobachevsky and Bolyai, each independent of the other, had marked the beginnings of non-Euclidean geometry, it was discovered that more than ten years previously, Gauss and Scheweikrat, each independent of the other, had arrived at the same results. To look at the sketches of the four scientists, who were each working unknown to the others, and to see that there seem to be traces of a single hand, gives a strange impression.

Without intending it, one comes to think that such a surprising and mysterious activity taking place over some millennia cannot be chance and must have a purpose. But given this, we must necessarily raise the question: what is this purpose?

. . . Mathematics grows impetuously and incessantly without the reworkings and crises typical of physics, continually enriching itself with new ideas and concrete facts. I am profoundly convinced that the achievements of present-day mathematics are no less perfect than the works of the classical mathematicians of the nineteenth, eighteenth, or seventeenth centuries, and that they can indeed stand comparison with the fruits of the Greek genius; but even the finest present-day achievements do not in fact surpass the classical ones at their best. What is the point of accumulating to infinity ideas that are equally profound? In doing this, doesn't mathematics transform itself in a fine and surprising variant of Hegel's "bad infinity"? Every activity without a purpose loses its meaning, and if we compare humanity with a living organism, mathematics proves to resemble a reasonable and sensible activity. It seems more like instinctive actions that can be repeated in a stereotyped way until an external or internal stimulus acts on them. If mathematics has no purpose, it cannot even elaborate a conception of itself, and as an ideal, all that is left is a growth regulated by nothing or, better, an expansion in all directions. To make another comparison, it can be said that the development of mathematics is not like the growth of a living organism which maintains its own form and establishes its own limits: rather, we have the growth of a crystal or the diffusion of a gas that can expand to an unlimited degree until they encounter an external obstacle.

Evidently a similar growth contradicts the sensation of rationality and beauty which inevitably arises in contact with mathematics, just as a magnificent symphony cannot continue ad infinitum.

. . . A history of more than two millennia teaches that mathematics does not seem to be in a position to formulate itself the final purpose that could direct its development. Hence this purpose has to be borrowed from outside. . . . It is possible to derive the purpose of mathematics from its practical applications. But it is difficult to believe that a superior spiritual activity can find its own justification in an inferior material quality. . . . The first theorems of Thales of Miletus established truths evident to any right-thinking person, such as that the diameter divides the circle into two equal parts. Genius was not necessary to convince oneself of the truths of these theses, but to understand them they needed to be demonstrated. It is evident that the practical value of such discoveries is zero. Even in our time, however varied and profound its applications, mathematics has not had its greatest successes under their influence. And then how are we to expect that the applications will confer on mathematics the purpose that it was not in a position to discover with its own forces?

So if we discard this line, one possibility seems to me to remain: a sphere of human activity that is not inferior but superior, namely religion, can confer a purpose on mathematics.

Today it is certainly difficult to imagine how that could come about, but it is even more difficult to think how mathematics could evolve ad infinitum without knowing the what and why of what it is studying. It will already perish in the course of the next generation, submerged in the sea of publications! And this is again the most elementary, exterior cause.

On the other hand, the solution indicated above is possible, as history has demonstrated. If we turn once again to the era in which mathematics emerged, we see that at that time it knew its own purpose and drew it from the force that I have mentioned. Mathematics was constituted as a science in the sixth century BCE in the religious confraternity of the Pythagoreans and was part of this. It had a clear purpose: it was the method for fusing with the deity by achieving the harmony of the world expressed in the harmony of numbers. Precisely this lofty aim conferred at that time the energies necessary for this scientific achievement which cannot be equaled: not the discovery of a magnificent theorem, nor the creation of a new sector of mathematics, but the creation of mathematics itself.

At that time, as it were at the very instant of its birth, those qualities of mathematics were manifested by virtue of which in it, more than in any other field, the tendencies common to all humankind are revealed. Precisely for this reason mathematics at that time provided the model on which the fundamental principles of deductive science evolved.

Purpose and Religion: Exploring the Explorable and Quietly Venerating the Inexplorable

Human beings tend toward the whole truth: science is an aspect of this quest for the truth. To seek to know the features of the natural order is the scientist's particular way of paying homage to the Mystery. The call addressed by John Paul II to physicists during his visit to CERN in Geneva (June 15, 1982) fully emphasizes research as an expression of the greatness of the human being and is an invitation to live to the full the passion for discovery as an openness to the basic questions of all human beings: "You too bring to light the greatness and the mystery of this man. The greatness of his investigative power, his reason, his capacity to achieve a greater truth. . . . His mystery, also, and perhaps the incredible innovations in pure research into the nature of matter, are infinitely less important than the emotional newness of the attitude of the person who feels so small confronted with these discoveries. . . . You yourselves, physicists, must expend your energies and your competence here with the sole scientific methods of the natural sciences. But as human beings you cannot fail to put other fundamental, existential questions of which I have spoken, to which philosophical wisdom and faith responds. I wish you also in this sphere to be men of research . . . men open to the fullness of truth."

Can science make its contribution on the terrain of ultimate questions? Max Planck observes that the scope of science extends beyond the simple satisfying of an innate curiosity: the aim of trying to know the laws of nature has something to do with a deeper level of human experience, touches on that level that looks at the awareness that human beings have of themselves.

Max Planck[24]

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. . . .

And he whom good fortune has permitted to co-operate in the erection of the edifice of exact science will find his satisfaction and inner happiness, with our great poet Goethe, in the knowledge that he has explored the explorable and quietly venerates the inexplorable.

Questions such as "Where do we come from and where are we going?" "Who are we?" are inevitable and universal, and express that need for an exhaustive meaning that distinguishes the human level within nature. Scientific knowledge is like a thin blade of light that cannot claim to illuminate the object completely and therefore can't reach ultimate explanations. But its capacity to describe the structure and the history of the physical world helps to give human questions a cosmic dimension, in which the whole of creation is carried along.

Erwin Schrödinger[25]

You could ask me, you are now forced to ask me: what in your view is the value of the natural sciences? I reply: their objective, purpose, and value are the same as any branch of human knowledge. None of these branches in itself has a purpose or a value, but only the union of all the branches of knowledge has meaning or value, and it can be defined quite simply: it is to obey the commandment of the Delphic oracle, "Know yourself." Or to put it in Plotinus's synthetic, expressive style: "And who are we?" . . .

I am born in a certain region. I do not know where I came from nor where I am going nor who I am. That is my situation, like yours, like that of each one of us. The fact that we are all in this same situation and always will be tells me nothing. The question which arises here is where we come from and where we are going, all that we can observe ourselves and what actually surrounds us. It is for this reason that we are anxious to discover as much about it as we can. That is science, to learn, to know; that is the rising truth of every spiritual human enterprise. We seek to discover as much as we can about the spatial and temporal environment of the place in which we find ourselves put by birth. And we find pleasure in the attempt, we find it extremely interesting. (Cannot this be the purpose for which we exist?)

It seems obvious and evident, but it should be said: the isolated knowledge attained by a group of specialists in a restricted sphere does not in fact have value in itself but only in synthesis with the rest of knowledge, only in that in this synthesis they really make a contribution through some things by answering the question, "Who are we?"

According to Weisskopf, the labors of the scientist are supported by the sense of a meaning in things.

Victor F. Weisskopf[26]

In what sense does the universe make sense? In the sense you sense a sense. Every true scientist feels a sense, consciously or unconsciously. If he did not, he would not go ahead, with that fervour so common among scientists, in his search for something that he calls the truth. Surely a large dose of ambition is mixed into the fervour—acclaim, tenure, a Nobel Prize—but there is no denying that it exists. It is based upon a conviction that what the scientist does is worthwhile and will lead to an increase of insight, something that is great and valuable beyond.

According to the Nobel Prize–winner Carlo Rubbia, not only does the "ultimate" question have its legitimate place in the rational mind of the scientist, but it also constitutes "the greatest form of freedom," and if one renounces it one is condemned to a state of "dehumanization" and "self-punishment."

Carlo Rubbia[27]

The greatest form of freedom is that of being able to ask where we come from and where we are going. This freedom allows you to put the question to yourself in a way which is honest and clear, but calm and serene, in that it is not an emergency question. It has nothing to do with those urgent procedures which must be "dealt with in case of." It is far too beautiful and profound to be disturbed by immediate interests. The problem is inscribed on our intellectual baggage, whether we like it or not. There is no form of human life that does not pose this question. And there is no form of human society that has not sought in some way to give an answer. The lack of this involvement is a loss, a dehumanization, an internal mechanism of self-punishment.

What is most impressive about the question is its universality: it is common to all. Put in this room ten people who do not know one another, of different cultures, religions, ages, histories. Put a hundred in a square, a thousand in a countryside, millions in a city. Billions. What do they have in common, if not this question? All raise this question or can do. All are looking for an answer, and the answers will be ten, a hundred, a thousand, or millions, each different from the other. What basically counts is the common question, rather than the answer. The answer doesn't count for much. Also because we know very well that we shall never know this answer.

If we will never know the right answer—and it is precisely here, in this mystery, that all its fascination lies—there will be many answers from people. As many as there are people on earth. For each of us the answer that we give will be the right one. I do not see why a reply A is better or worse than a reply B. I cannot see why.

I believe that all this is part of our ethical baggage, and I think that what counts is respect for our humanity, the fact that we are human beings. And since we all think that our being human is something that puts us above all other living beings on earth, we must necessarily also think that we are made in the image of something yet more important than us. It is difficult, almost impossible, not to believe. It is even inevitable, so inevitable that I think that it is written within us.

I do not see how one cannot say yes to the existence of something additional. I am an optimist; it is easy for me to believe this. Moreover, there is no need to be optimistic; it is enough to be good observers. As Einstein once said, God is distributed in nature. That is indeed the case, I am more than certain of that. Nature is constructed in such a way that there is no question that it is constructed by chance. The more one studies the phenomena of nature, the more deeply one is convinced of this. There are natural laws of an incredible depth and beauty. It can no longer be thought that all this can be reduced to an accumulation of molecules. The scientist in particular fundamentally recognizes the existence of a law that transcends, something that is outside and imminent in the natural mechanism. Recognize that this "something" is the cause that organizes the system.

It is "something" that escapes us. The more we look within, the more we understand that it has nothing to do with chance. I often give the example of that kind of mysticism which seizes one on a starry night. The same mechanism of wonder, one might almost say religion, seizes us when, rather than looking at the stars from a long way off, we look at them from within. This very sentiment that we feel when looking at the stars from afar increases, becomes even more concrete. The feeling that a secular person has when observing a great natural phenomenon such as a starry sky, a sunset, the vastness of the sea, is even greater for scientists in that they see something truly perfect in its structure. This perfection exists, is in the depth of things. It is not a shadow, it is not an apparition.

. . . Scientists observe nature in its most perfect form, and have to do so with intelligence, modesty, goodness. He must make himself very small, as when one is watching a wild animal moving freely and happily in the forest. I feel profoundly honored to be able to watch, to be able to understand. Scientists can observe and appreciate something sublime. And they do so not only for themselves. They have the duty to transmit it to all the people in the world.

Therefore there is no antithesis between nature and the human being. Nature in its perfection leads one to think that it is not "chance." Scientists observe the physical laws, the laws of nature, and find that they are immutable in space and time. What is furthest possible from us in space and time all takes place as if it were happening under our eyes. We cannot claim that these laws are unique, immutable, precise, and perfect, and cannot fail to think that behind this mechanism of immutability and perfection there is something that guarantees stability. Order and stability in the natural laws cannot be arbitrary. There is something which ensures that this continuity is there. If we observe all that, we cannot but conclude that in some way there must be a mechanism, something superior, transcendent. ✺

Reason is led to affirm "something real," a "Quid," which ultimately governs the world. However, that "Quid" cannot be known solely by human capacities: the answer that human beings seek to give, their attempts to express or describe the Mystery, constitute a series of imperfect attempts.

Purpose and Morality: Bringing to Light the Union of the Finite with the Infinite

The purpose for which scientists work and sacrifice themselves is certainly not just their salaries and a peaceful career, but something that fascinates them and motivates them profoundly before and beyond these objectives. Over and above their merits, they are determined by a fascination and a tension with the truth, and this tension is what marks their typical behavior. It can then be said that only in a space of gratuitousness, decided assent, affection for the truth, can there be a fully human experience of scientific research.

Michael Faraday[28]

It puzzles me greatly to know what makes the successful philosopher. Is it industry and perseverance with a moderate proportion of good sense and intelligence? Is not a modest assurance of earnestness a requisite? Do not many fail because they look rather to the renown to be acquired than to the pure acquisition of knowledge, and the delight which the contented mind has in acquiring it for its own sake? I am sure I have seen many who would have been good and successful pursuers of science, and have gained themselves a high name, but that it was the name and the reward they were always looking forward to—the reward of the world's praise. In such there is always a shade of envy or regret over their minds, and I cannot imagine a man making discoveries in science under these feelings. As to Genius and its power, there may be cases; I suppose there are. I have looked long and often for a genius for our Laboratory, but have never found one. . . .

Henri Poincaré[29]

The Scientist does not study nature because it is useful to do so. He studies it because he takes pleasure in it; and he takes pleasure in it because it is beautiful.

If nature were not beautiful, it would not be worth knowing and life would not be worth living. . . . I mean the intimate beauty which comes from the harmonious order of its parts and which a pure intelligence can grasp. . . .

It is because simplicity and vastness are both beautiful that we seek by preference simple facts and vast facts; that we take delight now in following the giant courses of the stars, now in scrutinizing with a microscope that prodigious smallness which is also a vastness, and, now in seeking in geological ages the traces of the past that attracts us because of its remoteness.

Human beings are involved in the quest for the truth, open and passionate in their interest. As John Paul II recalled when speaking to university students: "Commitment to science is not an activity which relates only to the intellectual sphere. It involves the whole person. This person in fact launches out with all his strength in the quest for truth, precisely because the truth seems to him to be a good. So there is an indivisible correspondence between the truth and the good. This indicates that all human work has a moral dimension. In other words, in whatever we do—including study—we notice at the heart of our spirit a demand for fullness and unity."[30] The subject of knowledge is the whole person, and the work of the scientist also finds its values in an expression of the unity of the person.

James Clerk Maxwell[31]

Happy is the man who can recognize in the work of To-day a connected portion of the work of life, and an embodiment of the work of Eternity. The foundations of his confidence are unchangeable, for he has been made a partaker of Infinity. He strenuously works out his daily enterprises, because the present is given him for a possession.

Thus ought Man to be an impersonation of the divine process of nature, and to show forth the union of the infinite with the finite, not slighting his temporal existence, remembering that in it only is individual action possible, nor yet shutting out from his view that which is eternal, knowing that Time is a mystery which man cannot endure to contemplate until eternal Truth enlighten it.

Pavel A. Florensky[32]

I wanted to write to you about my work, or more precisely about its meaning, its inner substance, so that you can continue to take forward that thought which fate does not allow me to elaborate further and to pursue to its end. . . . What have I been doing all my life? I have been contemplating the world as a whole, as a picture and a compact reality, but at every stage of my life from a particular point of view. . . . Its perspectives change, one enriching the other, and this is the reason for the continual dialectic of thought together with a constant orientation on seeing the word as a single whole.

Oliver Sacks[33]

Science sometimes sees itself as impersonal, as "pure thought," independent of its historical and human origins. It is often taught as if it were the case. But science is a human enterprise through and through, an organic, evolving, human growth, with sudden spurts and arrests, and strange deviations, too. It grows out of its past, but never outgrows it, any more than we outgrow our own childhood.

Michael Polanyi[34]

There are no rigorous rules for discovering things that are bound up with nature, nor even for saying that we must accept or reject an apparent coherence as a natural fact. There is always a residue of personal judgment that enters into deciding whether or not to accept a particular observation, either as proof of a true regularity or on the contrary as a refutation of the apparent regularity. And in this way I have seen and accepted the fact that strictly speaking the whole of empirical science is imprecise; and gradually I have noted that all its integration is, like perception, based to a large degree on tacit elements, of which we have only a vague knowledge. I have applied this also to science and declared that science is based on an act of personal judgment: and that is why I would call this knowledge personal knowledge.

The right attitude for confronting the scope of scientific activity and the problems that this activity raises has been outlined with his usual effectiveness by Ennio De Giorgi: humility and greatness of soul. But sometimes wisdom encounters an unexpected coincidence.

Ennio De Giorgi[35]

A reminder of the oldest roots of wisdom might seem out of place as an answer to the problems posed by the developments of science and modern technology, but I believe that if we want, if not to resolve such problems, at least to take a correct approach to them, we must put them in a very broad perspective which embraces the most concrete and lowliest realities as well as the highest and most abstract ones. It seems to me that this perspective is that of the book of Proverbs, which speaks at length of the most common human conditions and finally of the life of the smallest and most common animals, and in which Wisdom herself says of herself that she was with the Lord at the beginning, before the creation of the world, which delighted in this creation and loves to stand with the sons of men (cf. Prov. 8:22–31).

I think that the broad wisdom perspective of the book of Proverbs is the best perspective for those considering the problems of modern science; the complex relations between science, ethics, economics, and politics; the antinomies and paradoxes that present themselves in the study of the fundamentals of mathematics and the other scientific disciplines, those which are usually called "the limits of science," and I consider these rather to be signs of the infinite greatness of reality, visible and invisible. I think that Shakespeare expressed this greatness better than any scientist when he said in *Hamlet*: "There are more things in heaven and earth than are dreamed of in your philosophy."

With these observations I do not claim to have answered the questions . . . about scientific progress and the future of humanity, but perhaps I have indicated a way that could be followed by those who would like to meditate on it, the way of humility and hope traced in the book of Proverbs. This, while inviting us to seek wisdom with trust, teaches us to distrust those persons who believe themselves to be wise, recalling that the wise man hears his critics attentively and gratefully (cf. Prov. 9:9).

In the activity of the teacher and researcher, to follow the way of humility and hope means to carry out one's specialist researches with scrupulous methodology, to communicate with simplicity to all those who may be interested in the successes achieved, the failed attempts and the difficulties encountered; to prepare lectures and exercises with care; to perform with patience, impartiality, humanity, common sense, the ungrateful but necessary duty of marking examinations, judging competitions, dealing with requests for study grants, prizes, etc. At the same time this daily duty must be combined with a constant curiosity and a constant desire to learn new things, since no one who does not himself have the desire to learn can be a good teacher, nor can anyone who is not animated by this sentiment transmit to others the love of wisdom. The humility and commitment to daily work must be combined with an attitude of respect and attention to every branch of knowledge, since in life everyone succeeds in informing themselves only on a limited number of subjects, but can and must love all of wisdom in the broadest sense of the word.

On the other hand, the humility of the serious scientific researcher must be combined with a certain "greatness of spirit," with the joy of "contemplating" the most difficult and interesting problems on which the best scholars have labored for decades (or even centuries) to speak about them serenely with friends, colleagues, and pupils. I think that without this "greatness of spirit" teaching becomes narrow-minded and monotonous, scientific research never achieves really significant results, and that only those who set out with elevated objectives can gain results of any interest.

The good "servant of Wisdom" honestly recognizes the limits of his intelligence and his culture and pursues his own everyday work with modesty and patience, but he does not exclude the possibility that this same Wisdom will come to meet him with an unexpected coincidence, a fortunate observation, a happy intuition. Sometimes Wisdom comes to meet us in an unpredictable way through a series of failed attempts, of fruitless researches, which make us think of the need for new ideas, for a major change in the formulation of problems and the method with which we seek to resolve them.

Purpose and Faith: There Are No Conflicts to Be Reconciled

Science, as we have noted, had its historical roots in Christian soil, and this is probably not just a chance coincidence. The Christian mentality has also accompanied and supported the human and scientific experience of a large number of its protagonists in succeeding centuries. On July 21, 1969, shortly after the historic landing of American astronauts on the moon, Paul VI said: "Observe the panorama of heaven and the world; measure, if you can, its vastness; have an idea of the density of the real, the true, the hidden that is contained in it; feel a shiver of marvel at the boundless greatness that you have before you; assert the irreducible difference between God the creator and the created world and together recognize, confess, celebrate the indissoluble nature which unites the creation with its creator."[36] This sympathetic impulse and capacity for identification demonstrate how supportive is the Christian mentality to the desire of human beings to know and understand the world.

The presumed difficulty, or indeed impossibility, of reconciling scientific knowledge and religious faith is quite extraneous to the experience of numerous scientists who believe consciously and critically.

We shall give just some examples here.

Georges Lemaître[37]

Nothing in my working life, nothing that I have ever learned in my studies of either science or religion, has ever caused me to change that opinion [that truth can be arrived at in two ways: "from the standpoint of salvation and from the standpoint of scientific certainty"]. I have no conflict to reconcile. Science has not shaken my faith in religion, and religion has never caused me to question the conclusions I reached by strictly scientific methods. ✺

Georges Lemaître[38]

Both . . . the scientist-believer and the scientist non-believer attempt at decoding the palimpsest of nature with multiple imbrications in which the traces of the various stages of the world's lengthy evolution has been overlapped and blended. The believer perhaps has an advantage of knowing that the riddle possesses an intelligent being, and consequently that the problem proposed by nature has been posed in order to be solved, therefore, that its degree of difficulty is presumably commeasurable with the present and future capacities of humanity. Perhaps the awareness of this will not give any new means in his investigation but this will contribute to sustain him in this healthy optimism without which a necessary effort would not be maintained for a longer time. ✺

Michael Faraday[39]

Even in earthly questions I believe that "the invisible things of him from the creation of the world are clearly seen, being understood by the things that are made, even his eternal power and Godhead" (cf. Rom. 1:20); and I have never seen anything incompatible between the things of man that can be understood by means of the spirit of man that is in man and the higher things regarding his future which he cannot know by means of that spirit.

These observations . . . are thus immediately connected in their nature and origin with my life as an experimenter, that I thought that the conclusion of this volume (*Experimental Research in Chemistry and Physics*) is not a suitable place for reproducing them. ✺

Often science has been (and in certain circles still is) used ideologically in an attempt to deny the reality of the Mystery, doing what Du Noüy calls "vile and anti-scientific work." He is someone who has succeeded in going against the current by following the ways of science, with great difficulties.

Pierre Lecomte du Noüy[40]

Those who without any proof—I have demonstrated this elsewhere—have systematically worked to destroy the idea of God have done a vile and anti-scientific work. And I proclaim this with all the greater force and conviction in that I do not possess the faith, that true faith which derives from the depth of being. I do not believe more in God than those who believe in the reality of evolution or in the reality of electrons. . . . Rather than being, like other scientists whom I envy, supported, helped by an irremovable belief in God, I started out in life with the destructive skepticism which was then in fashion. It took me thirty years of laboratory work to succeed in convincing myself that those who had the duty to illuminate me, if they did not confess their ignorance, had deliberately lied to me. My conviction today is rational. It has been reached through the paths of biology and physics, and I am convinced that it is impossible for any student who reflects not to end up arriving at it, if he is not blind or in bad faith. But the way that I have followed is tortuous, it is not the best. And it is to help others to avoid the vast waste of time and effort that I have suffered, that I have violently set myself against the malevolent spirit of these evil pastors. ✺

The great astronomer Allan Sandage is clear about the distinction between the methods of knowledge proper to science and to faith, a distinction of method that derives from the different objects that scientists desire to know.

Allan Sandage[41]

Q. Must there necessarily be a conflict between science and religion?

In my opinion, no, if it is understood that each treats a different aspect of reality. The Bible is certainly not a book of science. One does not study it to find the intensities and the wavelengths of the Balmer spectral lines of hydrogen. But neither is science concerned with the ultimate spiritual properties of the world, which are also real.

Science makes explicit the quite incredible natural order, the interconnections at many levels between the laws of physics, the chemical reactions in the biological processes of life, etc. But science can answer only a fixed type of question. It is concerned with the *what*, *when*, and *how*. It does not, and indeed cannot, answer within its method (powerful as that method is), *why*.

Why is there something instead of nothing? Why do all electrons have the same charge and mass? Why is the design that we see everywhere so truly miraculous? Why are so many processes so deeply interconnected?

But we must admit that those scientists that *want* to see design *will* see design. Those that are content in every part of their being to live as materialistic reductionalists (*as we must all do as scientists in the laboratory, which is the place of the practice of our craft*) will never admit to a mystery of the design they see, always putting off by one step at a time, awaiting a reductionalist explanation for the present unknown. But to take this reductionalist belief to the deepest level and to an indefinite time into the future (and it will always remain indefinite) when "science will know everything" is itself an act of faith which denies that there can be anything unknown to science, even in principle. But things of the spirit are not things of science.

There need be no conflict between science and religion if each appreciates its own boundaries and if each takes seriously the claims of the other. The proven success of science simply cannot be ignored by the church. But neither can the church's claim to explain the world at the very deepest level be dismissed. If God did not exist, science would have to (and indeed has) invent the concept to explain what it is discovering at its core. Abelard's twelfth-century dictum "Truth cannot be contrary to truth. The findings of reason must agree with the truths of scripture, else the God who gave us both has deceived us with one or the other" still rings true.

If there is no God, nothing makes sense. The atheist's case is based on a deception they wish to play upon themselves that follows already from their initial premise. And if there *is* a God, he must be true both to science and religion. If it seems not so, then one's hermeneutics (either the pastor's or the scientist's) must be wrong.

I believe there is a clear, heavy, and immediate responsibility for the church to understand and to believe in the extraordinary results and claims of science. Its success is simply too evident and visible to ignore. It is likewise incumbent upon scientists to understand that science is incapable, because of the limitations of its method by reason alone, to explain and to understand *everything* about reality. If the world must simply be understood by a materialistic reductionalist nihilism, it would make no sense at all. For this, Romans 1:19–21 seems profound. And the deeper any scientist pushes his work, the more profound it does indeed become.

Q. Do recent astronomical discoveries have theological significance?

I would say not, although the discovery of the expansion of the Universe with its consequences concerning the possibility that astronomers have identified the creation event does put astronomical cosmology close to the type of medieval natural theology that attempted to find God by identifying the first cause. Astronomers may have found the first effect, but not, thereby, necessarily the first cause sought by Anselm and Aquinas.

Nevertheless, there are serious scientific papers discussing events very shortly after the big bang creation (ex nihilo?) out of which all the types of matter that we know (baryons, electrons, photons, etc.) were made, and in what quantities. Even the creation of matter is said now to be understood. Astronomical observations have also suggested that this creation event, signaled by the expansion of the Universe, has happened only once. The expansion will continue forever, the Universe will not collapse upon itself, and therefore this type of creation will not happen again.

But knowledge of the creation is *not* knowledge of the creator, nor do any astronomical findings tell us why the event occurred. It is truly supernatural (i.e., outside our understanding of the natural order of things), and by this definition a miracle. But the nature of God is not to be found within any part of these findings of science. For that, one must turn to the scriptures, if indeed an answer is to be had within our finite human understanding.

Q. Can a person be a scientist and also be a Christian?

Yes. As I said before, the world is too complicated in all its parts and interconnections to be due to chance alone. I am convinced that the existence of life with all its order in each of its organisms is simply too well put together. Each part of a living thing depends on all its other parts to function. How does each part know? How is each part specified at conception? The more one learns of biochemistry the more unbelievable it becomes unless there is some type of organizing principle—an architect for believers—a mystery to be solved by science (even as to *why*) sometime in the indefinite future for materialist reductionalists.

This situation of the complication and the order to function of an organism, where the sum is greater than its parts (i.e., has a higher order), becomes more astonishing every year as the scientific results become more detailed. Because of this, many scientists are now driven to faith by their very work. In the final analysis it is a faith made stronger through the argument by design. I simply do not now believe that the reductionalist philosophy, so necessary to pursue the scientific method and, to repeat, the method which all scientists must master and practice with all their might and skill in their laboratory, can explain everything.

Having, then, been forced via the route of Pascal and Kierkegaard in their need for purpose to come to the edge of the abyss of reason, scientists can, with Anselm "believe in order to understand" what they see, rather than "understand in order to believe."

Purpose and Praise: In Wisdom Hast Thou Made Them All!

For the scientist who has encountered the Christian event, every fragment of knowledge of the created world is an occasion for gratitude, for celebration and praise of the King of the universe. Many great scientists have expressed this praise of the Creator openly and in a passionate way at the culmination of their scientific life, identifying in it the ultimate purpose and satisfaction of their research. Their testimony is an unusual and moving affirmation of Christ, Lord of the universe and the destiny of all things.

Nicolaus Copernicus[42]

Among the many and varied literary and artistic studies upon which the natural talents of man are nourished, I think that those above all should be embraced and pursued with the most loving care which have to do with things that are very beautiful and very worthy of knowledge. Such studies are those which deal with the godlike circular movements of the world and the course of the stars, their magnitudes, distances, risings and settings, and the causes of the other appearances in the heavens; and which finally explicate the whole form. For what could be more beautiful than the heavens which contain all beautiful things? . . . For who, after applying himself to things which he sees established in the best order and directed by divine ruling, would not through diligent contemplation of them and through a certain habituation be awakened to that which is best and would not wonder at the Artificer of all things, in Whom is all happiness and every good? For the divine Psalmist surely did not say gratuitously that he took pleasure in the workings of God and rejoiced in the works of His hands, unless by means of these things as some sort of vehicle we are transported to the contemplation of the highest Good.

Robert Boyle[43]

When with bold telescopes I survey the old and newly discovered stars and planets, that adorn the upper region of the world; and when with excellent microscopes I discern, in otherwise invisible objects, the unimitable subtility of nature's curious workmanship; and when, in a word, by the help of anatomical knives, and the light of chymical furnaces, I study the book of nature . . . : I find myself oftentimes reduced to exclaim with the Psalmist, How manifold are Thy works, O Lord! In wisdom hast Thou made them all!". . .

The next advantage . . . that we mentioned the knowledge of nature to bring to the minds of men, is, that there it excites and cherishes devotion. . . .

Now if you should put me upon telling you . . . what those attributes of God are, which I so often mention to be visibly displayed in the fabrick of the world, I can readily answer you, that though many of God's attributes are legible in his creatures, yet those, that are most conspicuous there, are his power, his wisdom, and his goodness, in which the world, as well as the Bible, though in a differing, and in some points a darker way, is designed to instruct us. . . .

Enrico Medi[44]

Oh you mysterious galaxies! You send light but do not intend light; you send flashes of beauty but do not possess beauty; you have immensity of size but do not calculate size. I see you, calculate you, look at you, study you and discover you, penetrate you and absorb you. From you I take light and make it science, I take motion and make it wisdom, I take the flickering of the colors and make poetry of them; I take you stars in my hands and, trembling in the humility of my being, I ascend above you and I pray to that Creator whom only through me can you stars worship. Man is greater than the stars. Behold our immense dignity, the immense greatness of man! Young people, enjoy this gift which has been given to you and was given to us. . . . From one thing may God protect you, from skepticism, criticism, and cynicism; the young person contemptuous of all things is an old man who has risen from the tomb. Woe if youth loses the enchantment of enthusiasm. ✺

James Clerk Maxwell[45]

Omnipotent God, who has created man in your image and has made him a living spirit so that he can seek and have power over your creatures, teach us to study the work of your hands in such a way that we can subject the earth to our use and strengthen our reason in your service, and receive your blessed word, so as to have faith in the one whom you have sent to give knowledge of salvation and the remission of our sins. ✺

Johannes Kepler[46]

I break off the dream and the very vast speculation, merely crying out with the royal Psalmist: Great is our Lord and great His virtue and of His wisdom there is no number: praise Him, ye heavens, praise Him, ye sun, moon, and planets, use every sense for perceiving, every tongue for declaring your Creator. Praise Him, ye celestial harmonies, praise Him, ye judges of the harmonies uncovered . . . : and thou my soul, praise the Lord thy Creator, as long as I shall be: for out of Him and through Him and in Him are all things (both the sensible and the intelligible); for both those whereof we are utterly ignorant and those which we know are the least part of them; because there is still more beyond. To Him be praise, honour, and glory, world without end. Amen. ✺

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Appendix A
Biographical Notes

Albertus Magnus (Lauingen, Germany, 1193–Cologne 1280)
A pioneer in the observation of nature, a Dominican philosopher and theologian, he taught at the University of Paris and was the teacher of Thomas Aquinas. Canonized in 1931 by Pius XI, in 1941 he was nominated patron saint of scientists by Pius XII. He maintained the superiority of evidence based on sensory perception over that obtained by reason and asserted the inconsistency of principles not encountered in experience. One of his prime assertions was the need to repeat an experiment many times in the most varied circumstances to ensure its validity. His *De vegetalibus et plantis* remains a model scientific treatise for the accuracy of its descriptions and the systematization of the classifications proposed.

Al-Biruni (Khiva, Uzbekistan, 973–Ghazni, Afghanistan, 1048)
One of the greatest scientists of the Islamic world, he was a mathematician, astronomer, physicist, geographer, and pharmacologist, but was also occupied with history, philosophy, and poetry. He was admitted at a very young age to the Academy of Ma'mun, where he came into contact with Avicenna and other cultured Islamic figures of the period. He translated Euclid's *Elements* into Sanskrit and, after a long journey, wrote his most famous book, *Description of India*. His work had a great influence on Eastern science. Among the twenty-seven writings which have come down to us (of more than five hundred), mention should be made of *Pharmacopia*, *Gems*, and *The Canon of Ma'udi on Astronomy*.

Edoardo Amaldi (Carpaneto, Italy, 1908–Rome 1989)
A physicist, he was a member of the famous Via Panisperna group, led by Enrico Fermi. Professor of physics at the University of Rome, he was one of the main protagonists in the creation of CERN in Geneva and its secretary-general. In his last years he devoted himself to building an antenna to reveal gravitational waves. He was very active in various organizations promoting disarmament and international collaboration.

Archimedes (Syracuse, Sicily, 287 BCE–Syracuse 212 BCE)
A Greek mathematician, physicist, engineer, astronomer, and inventor, he spent all his life in Syracuse and was a personal friend of the local sovereign Hiero II and Hiero's son Gelo. He died during the Roman siege of the city, killed by accident by a legionary who did not recognize him. He is considered the greatest scientist of antiquity; in addition to his studies of pure mathematics, he obtained notable results in the practical application of his own theories' results. His fame is linked to "Archimedes principle," according to which a body immersed in a fluid is buoyed up by a force equal to the weight of the displaced fluid.

John Barrow (London 1952–)
A cosmologist of great international fame, from 1989 to 1999 he taught astronomy and was director of the Centre of Astronomy at the University of Sussex. From 1999 he has been research professor of mathematical science at Cambridge and director of the Millennium Mathematics Project, an initiative created to spread the teaching of mathematics and its applications. Author of more than three hundred publications on astronomy and astrophysics, he is also known as a brilliant scientific popularizer; his numerous highly successful books include *The Left Hand of Creation: Origin and Evolution of the Expanding Universe* (1988, with Frank Tipler), *The World within the World* (1988), and *Pi in the Sky: Counting, Thinking and Being* (1993).

Susan Jocelyn Bell Burnell (Belfast 1943–)
An astronomer and famous for—while a student—having discovered pulsars, heavenly bodies whose appearance was completely unexpected since they did not fit into the theoretical context of the time (the Nobel Prize for their discovery was given to the supervisor of her thesis, Anthony Ewish). After gaining a PhD in radio astronomy at Cambridge, she has worked at University College,

London and the Royal Observatory of Edinburgh and has taught physics at the Open University. She has received the Oppenheimer Prize and the Michelson Medal.

Claude Bernard (Saint-Julien, France, 1813–Paris 1878)
He was a physicist, endocrinologist, pathologist, and epistemologist. Four basic findings derive from his research: the digestive functions of the pancreas, the vaso-motor system, the effect of curare on neuromuscular transmission, and the glycogenetic function of the liver. Considered the father of experimental medicine, he summed up his methodological principles in the *Introduction to the Study of Experimental Medicine*, in which he sought a critical synthesis between mechanism and vitalism, and between experimentalism and rationalism.

Edoardo Boncinelli (Rodi, Greece, 1942–)
A physicist by training, he dedicated himself to the study of genetics and molecular biology, making fundamental contributions to the understanding of biological mechanisms in the embryonic developments of superior animals and human beings. He is currently director of the Scuola Internazionale Superiore di Studi Avanzati di Trieste, having been head of the Laboratory of Molecular Biology in the department of neuroscience at the San Raffaele Scientific Institute of Milan and having taught general biology and genetics at the University Vita Salute of Milan.

Robert Boyle (Lismore Castle, Ireland, 1627–London 1691)
He was involved in physics and chemistry and particularly studied the behavior of gases, arriving at the famous law that bears his name. He attacked the chemical conceptions of the alchemists and the Aristotelians, and developed a method of analysis that is the basis for modern chemistry, succeeding among other things in classifying the components into three categories: acids, bases and salts. His basic work is entitled *The Sceptical Chemist*.

Vannevar Bush (Everett, Massachusetts, 1890–Everett 1974)
He was a prominent scientist, advisor to various U.S. presidents, and the principal promoter of the creation of the National Science Foundation. After studying at Tufts College in 1913, he taught in the school for a number of years, pursuing research activities at the same time. In 1919 he became professor

at the Massachusetts Institute of Technology (MIT), where he remained for twenty-five years. In the 1940s he coordinated U.S. military research projects with research in various universities including MIT, Harvard, and UC–Berkeley. In 1945 he published an article that inspired many of the pioneers of the Internet.

Alexis Carrel (Sainte-Foy-lès-Lyon, France, 1873–Paris 1944)
After graduating in medicine he first worked in the hospital of Lyons and, from the beginning of the twentieth century, at the New York Rockefeller Institute, where he devoted himself to research in vascular surgery. A freethinker and skeptic, while with the sick in Lourdes he witnessed a miracle: he took a rigorous and objective attitude to it, incurring the hostility of the university and political world and compromising his career in France. In 1912 he gained the Nobel Prize for medicine and physiology.

James Chadwick (Bollington, U.K., 1891–Pinehurst, U.K., 1974)
After graduating in physics at Manchester, he worked as an assistant to E. Rutherford at the Cavendish Laboratory. In 1932 he made the important discovery of the existence of neutrons, correctly reinterpreting the experimental results obtained by W. W. G. Bothe and I. and F. Joliot-Curie. Three years later, he was awarded the Nobel Prize for physics. As head of the British scientific delegation in the United States, he played an active part in the development of the Manhattan Project.

Subrahmanyan Chandrasekhar (Lahore, India, 1910–Chicago 1995)
An astrophysicist, after graduating at the University of Madras he pursued his studies in England, gaining a PhD at Cambridge. After some years at Trinity College, he moved to the United States and in 1952 occupied the prestigious chair of theoretical astrophysics at the Institute for Nuclear Studies in Chicago. He is known above all for his researches into stellar evolution and in particular for his theory of gravitational collapse and white dwarfs; for this he was awarded the Nobel Prize for physics in 1983 (with W. A. Fowler).

Nicolaus Copernicus (Torun, Poland, 1473–Frombork, Poland, 1543)
A physician, mathematician, and astronomer, he was appointed canon of Frombork cathedral after several years in Italy. He is known for the heliocentric theory of the solar system, which contrasted with the Ptolemaic model

and which he expounded in detail in the treatise *De Revolutionibus Orbium Coelestium*. Copernicus was able to see the first printed copy of his fundamental work, written over many years and constantly revised, only on his deathbed.

George V. Coyne (Baltimore, Maryland, 1933–)
A mathematician, astronomer, philosopher, theologian, and member of the Society of Jesus, he was ordained a priest in 1965. After working at the Lunar and Planetary Laboratory of the University of Arizona, in 1978 he became director of the Vatican Observatory. His researches have concentrated on polarimetric analyses of various celestial objects such as the interstellar medium, the Seyfert galaxies, and interacting binary star systems. As director of the Vatican Observatory, he has organized numerous congresses on the relations between science and faith and has edited various publications, including (with R. Russell and W. Stoeger) *Physics, Philosophy and Theology, A Common Quest for Understanding* (1988).

Marie Curie (Warsaw 1867–Paris 1934)
She graduated in physics in Paris where, with her husband Pierre, she devoted herself to the study of radiation emitted by pitchblende, discovering radium and polonium in 1898. In 1902 she succeeded in isolating radium and for this in 1903 she was awarded the Nobel Prize for physics together with her husband and H. Becquerel. Her researches on radioactivity among other things led her to discover metallic radium, a discovery that also brought her the Nobel Prize for chemistry in 1911. She died a victim of radioactive contamination.

Nicolò Dallaporta (Trieste, Italy, 1910–Padova 2003)
He was professor emeritus of theoretical astrophysics in the University of Trieste, after holding the chair of theoretical physics at the University of Padua for more than twenty years and teaching theoretical astrophysics first at Padua and then at the Scuola Internazionale Superiore di Studi Avanzati di Trieste. After achieving important results in particle physics, he did much theoretical research into astrophysics and cosmology relating to stellar evolution, the origin and structure of the galaxies arising from high energy, and the primordial state of the big bang. Some of the principal Italian astrophysicists and cosmologists have been trained in his school. For many years he devoted himself to the study of relations between science and metaphysics.

Charles Darwin (Shrewsbury, U.K., 1809–Down, U.K., 1882)
After studying medicine at Edinburgh and theology at Cambridge, he devoted himself exclusively to the natural sciences. A sea voyage around the world with the ship *The Beagle*, lasting fifty-seven months, provided him with abundant material that formed the basis for his great work *The Origin of Species*, published in 1859; in it Darwin developed the new theory of evolution based on the concept of natural selection. His ideas were the starting point for further evolutionary theories that integrated later findings of biology and are still undergoing interesting developments. Because of its philosophical implications, from the beginning Darwinianism has been the object of debates and polemics, often on the basis of preconceived positions.

Paul Davies (London 1946–)
After holding academic posts at the Universities of Cambridge and London, he taught theoretical physics at the University of Newcastle upon Tyne. In 1990 he moved to Australia, where he became professor of mathematical physics at the University of Adelaide. In May 1993 the university created a personal chair in natural philosophy for him. He still teaches there and serves as associate director of the Institute of Physics. In 1995 he won the Templeton Prize. He is known for his intensive work as a popularizer through conferences and seminars throughout the world. His publications include *God and the New Physics* (1984) and *The Last Three Minutes* (1994).

Ennio De Giorgi (Lecce, Italy, 1928–Pisa 1996)
A mathematician, he became a key figure in world mathematics by completely resolving "Hilbert's 19th problem" at the age of twenty-eight. In 1959 he was called to the Scuola Normale di Pisa, where he remained and taught for about forty years. He was a member of various institutes and academies and received many honors, including an honorary doctorate at the Sorbonne and the Wolf Prize. He was distinguished for his marked civil commitment, above all in the field of the defense of human rights. A convinced supporter of the multidisciplinary aspect of culture, his last studies were concentrated on the foundation of science and the unity of knowledge.

Paul Dirac (Bristol, U.K., 1902–Tallahassee, Florida, 1984)
A theoretical physicist of great intellectual rigor, he was among the main protagonists of quantum physics, which he developed in a parallel but not

identical way to that of the Göttingen-Copenhagen school. In 1926 he reformulated the quantum statistics of electrons, which had previously been formulated by Enrico Fermi (subsequently known as the Fermi-Dirac statistics). Quantum theory relating to individual particles (with the famous Dirac equation) is his work; it led to the prediction (1931) of the existence of antimatter. The first antiparticle, the positron, was discovered later by Anderson. Dirac was awarded the Nobel Prize for physics in 1933 (with Erwin Schrödinger).

René Dubos (Saint-Brice, France, 1901–New York 1982)
A microbiologist, he migrated to America in 1924, where he gained his PhD at Rutgers University and then entered the Rockefeller Institute for Medical Research. In 1939 he isolated from the *bacillus brevis* a substance that he called tyrothicin, and later this stimulated the researches that led to the discovery of tetracycline. In 1986 he was awarded the Pulitzer Prize for his book *So Human an Animal*.

Pierre Duhem (Paris 1861–Cabrespine, France, 1916)
A physicist, epistemologist, and historian of French science, he was ordinary professor of theoretical physics at Bordeaux from 1893. He made original contributions in thermodynamics and fluid mechanics, but is better known as an epistemologist and a historian of physics. A key element in his epistemology, often simplistically associated with the conventionalist school, is the thesis of historical continuity. This manifests itself particularly in his proposal to revalue the importance of medieval science, into which he pioneered systematic research. His books include *La théorie physique* (1906) and the ten volumes of *Le système du monde: Histoire des doctrines cosmologiques de Platon à Copernic*, begun in 1913 and completed by his daughter Hélène after his death.

Renato Dulbecco (Catanzaro, Italy, 1914–)
He graduated in medicine at the University of Turin, where as study companions he had the future Nobel Prize–winners Salvador Luria and Rita Levi Montalcini. In 1947 he moved to the United States, where he did research at the University of Indiana at Bloomington and Caltech (Pasadena). After some years at the Imperial Cancer Research Fund, he returned to California to the Salk Institute of La Jolla. In 1964 he won the Lasker Prize and in 1975 the Nobel Prize for medicine (with David Baltimore and Howard Temin) for research into the interaction between tumor viruses and the genetic material of the cell.

In 1986 he launched the Human Genome Project, with the aim of deciphering the human genetic patrimony.

Freeman Dyson (Crowthorne, U.K., 1923–)
A theoretical physicist, he has made original contributions to the formulation of quantum electrodynamics. From 1948 he worked at the Institute for Advanced Studies at Princeton, but he was also occupied in the civil use of nuclear energy and took part in projects related to the U.S. space program. A brilliant popularizer, in particular in his book *Disturbing the Universe* (1979), he has offered a striking picture of the contemporary scientific world and the human aspects of the experience of a researcher. In 2000 he was awarded the Templeton Prize.

John Eccles (Melbourne, Australia, 1903–Lugano, Switzerland, 1997)
One of the most authoritative neurophysiologists of the twentieth century, he was awarded the Nobel Prize for medicine in 1963 (with A. L. Hodgkin and A. F. Huxley) for his studies on the mechanism of the ion connected with the excitation of the membrane of nervous cells. Together with Karl Popper he wrote *The Self and Its Brain* (1977) and is the author of two popular works, the titles of which sum up his conception of the human being as something more than and different from a pure biological machine and open to the metaphysical dimension: *The Human Mystery* (1979) and *The Wonder of Being Human* (1984).

Arthur Eddington (Kendal, U.K., 1882–Cambridge 1944)
He was a great figure in world astrophysics in the first half of the twentieth century. On the occasion of the total eclipse of the sun in 1919, he led one of the two expeditions organized to verify the effect predicted by the theory of relativity and was the first to report that the observations showed a convincing agreement with the theory, thus contributing to its loud affirmation. He also contributed to advancing studies on nucleosynthesis and stellar evolution. Struck by the numerous numerical coincidences between the universal constants, he tried to develop a "fundamental theory" to unify knowledge of the large-scale and small-scale structure of the universe.

Albert Einstein (Ulm, Germany, 1879–Princeton, New Jersey, 1955)
After graduating in mathematics and physics at Zurich Polytechnic, while he was employed by the Federal Patent Office in Berne in 1905, he published three

innovative articles on the special theory of relativity, the photoelectric effect, and Brownian motion. He taught theoretical physics at the Universities of Zurich and Prague and at the Prussian Academy. In 1916 he published his work on general relativity and in 1921 received the Nobel Prize for physics (not for relativity but for his studies on the photoelectric effect). Forced by Nazism to leave Germany, he transferred to Princeton, where he taught at the Institute for Advanced Studies until 1945. He published many works for the general public, effectively illustrating his theories and promoting his reflections on the cultural consequences of contemporary science.

Federigo Enrìques (Livorno, Italy, 1871–Rome 1946)
He was one of the greatest Italian mathematicians of the nineteenth/twentieth centuries, developing the theory and classification of algebraic surfaces almost from nothing. He taught geometry in the Universities of Bologna and Rome. He was president of the Italian Philosophical Society and of Mathesis; he edited the journals *Scientia* and *Periodico di matematiche* and the section on mathematics in the *Enciclopedia Italiana*. He made very important and authoritative contributions to the debates on the relationship between science and culture and its relevance in the training of the rising generations.

Leo Esaki (Osaka, Japan, 1925–)
A physicist, after gaining his PhD at the University of Tokyo he pursued his researches on semiconductors with the Sony Corporation, discovering the tunnel-effect diode, also called the "Esaki diode." Arriving in the United States in 1960 at the Thomas Watson Research Center of IBM, he pursued his studies on the applications of quantum physics to semiconductors. In 1973 he won the Nobel Prize for physics. He has been rector of the University of Tsukuba and is director of the Yamada Science Foundation and the Japan Science and Technology Foundation.

Michael Faraday (Newington, U.K., 1791–Hampton Court, U.K., 1867)
A physicist and chemist with great gifts of intuition and a capacity for experimentation, he is famous above all for his research into electromagnetic induction and electrolysis and for his intuitions into the concept of the field, then developed by Maxwell and Einstein. He systematically rejected honors and university chairs; as a member of the Royal Society of London, he dedicated himself with passion to the popularization of science.

Enrico Fermi (Rome 1901–Chicago 1954)
More than other great physicists of the past, he was able to combine notable capacities for both theoretical and experimental physics. Author of the first theories on weak reactions, he is known above all for his research in nuclear physics that led to the discovery of nuclear fission and its subsequent developments. For this research done in Rome as leader of the famous Via Panisperna group, Fermi was awarded the Nobel Prize for physics in 1938. To escape the racial laws he moved to the United States where, in 1942, under his direction at the University of Chicago, a controlled chain reaction was achieved in the first nuclear reactor in history. He took part in the Manhattan Project for the development of the first atomic bomb.

Richard Feynman (Far Rockaway, New York, 1918–Altadena, California, 1988)
A theoretical physicist, on the invitation of Oppenheimer he was the youngest member of the group that at Los Alamo completed the construction of the first atomic bomb. He was among the founders of quantum electrodynamics; he received the Einstein Prize for his researches in this field in 1954 and in 1965 the Nobel Prize for physics (with Julian Schwinder and Sin-Ititro Tomonaga). His approach to science, one of great originality, allowed him to introduce innovative points of view and elaborate methods of great effectiveness, such as the diagrams that bear his name. In his last years he reported his experiences and reflections in some attractive and lively popular books.

Alexander Fleming (Lochfield, U.K., 1881–London 1955)
A Scots bacteriologist, in 1928, when studying the behavior of the influenza virus, he discovered the property of some mold (*penicillium notatum*) capable of inhibiting the multiplication of bacteria. Following his discovery, the purification of penicillin by Howard W. Florey and the clinical experimentation made by Ernst B. Chain marked a decisive step in the struggle against infections. The three were awarded the Nobel Prize for medicine in 1945.

Pavel A. Florensky (Evlach, Azerbaijan, 1882–Solovetsky Islands, Russia, 1937)
A physicist and mathematician, he was ordained an Orthodox priest in 1911. He contributed to philosophical and theological journals and in 1914 published *The Pillar and Ground of the Truth: An Essay in Orthodox Theology in Twelve Letters*. After 1917 he dedicated himself to the history and theory of art; he taught the theory of perspective to Vchutemas, while continuing to publish

mathematical works. In 1921 he joined the Supreme Economic Council and edited the great *Technical Encyclopaedia*. Exiled in 1928 for his religious convictions, in 1933 he was arrested, condemned to ten years in a labor camp, and sent to the Solovetsky Islands, where he was executed as an "anti-Soviet element."

Galileo Galilei (Pisa, 1564–Arcetri, Italy, 1642)
He is considered the father of the experimental scientific method. After beginning to study medicine, from 1585 he dedicated himself completely to mathematics and physics, teaching first at Pisa and then at the University of Padua, where he did the first fundamental research into mechanics, discovering among other things the law of the fall of bodies. As an astronomer, by means of the telescope, which he reinvented, he made decisive discoveries that led him publicly to attack the theses of the Aristotelians and openly to support the heliocentricity of Copernicus. Despite repeated warnings to be prudent, and contravening a decree of the Holy Office, in 1632 he published his *Dialogue Concerning the Two Chief World Systems*, which affirmed, in a brilliant and polemical style, the absolute validity of the Copernican system. The process that inevitably followed ended with his recantation and house arrest in his villa at Arcetri, where, with his daughter Maria Celeste, he spent the last years of his life and could write his most important work of mechanics, *Discourses and Mathematical Demonstrations Relating to Two New Sciences*, a milestone in modern physics.

Karl Friedrich Gauss (Brunswick, Germany, 1777–Göttingen, Germany, 1855)
A mathematician, physicist, and astronomer, he was professor and director of the astronomical observatory of Göttingen, where he made important astronomical calculations and produced a complete theory of the motion of the solar system. He formulated the law of the distribution of chance errors, expressing it with the function represented by the classical form of a bell and subsequently called Gaussian. He conceived a geometry that disregarded Euclid's fifth postulate and which he called "non-Euclidean." In physics he expounded a general theory of terrestrial magnetism and laid the foundations of electrostatics.

Murray Gell-Mann (New York 1929–)
A theoretical physicist, he has taught at the University of Chicago and Caltech (Pasadena), where he is now professor emeritus in theoretical physics. He is

one of the founders and directors of the Santa Fe Institute, where adaptive systems are being studied. He was awarded the Nobel Prize for physics in 1969 for his theory of quarks (a term he coined); this marked a new branch of physics, quantum chromodynamics. The breadth of his interests (from archaeology and biological evolution to linguistics) is documented brilliantly in his *The Quark and the Jaguar* (1996).

Sheldon Lee Glashow (New York 1932–)
A physicist, he has worked in some of the main American and European centers of research on particle physics and the theories that point to the unification of all elementary forces. In 1970 with John Iliopoulos and Luciano Maiani he predicted the existence of the charm-type quark and indicated how to discover it. In 1979 he was awarded the Nobel Prize for physics with Abdul Salam and his schoolmate Steen Weinberg, "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, *inter alia*, the prediction of the weak neutral current." From 2002 he has been professor of mathematics and science at Boston University.

Charles Eugène Guye (Saint-Christophe, Switzerland, 1866–Geneva 1942)
A physicist, in collaboration with C. Lavanchy he carried out an experiment on the variations of the mass of the electron with velocity, using cathode rays with velocities between 0.2 and 0.5 times that in a vacuum, confirming the results of the experiments of A. H. Bucherer in support of the theory of relativity.

John Burdon Sanderson Haldane (Oxford, U.K., 1892–Buhbaneswar, India, 1964)
Son of the physiologist Scott Haldane, he was a geneticist, physiologist, biochemist, and biomathematician. He was among the pioneers of the application of mathematical techniques to biology, contributing to the foundation of population genetics. He was an important supporter of the English Communist Party, which he left at the time of the Lysenko case. In 1957 he moved to India, where he founded and directed the laboratory of genetics and biometry at Bhubanesdwar.

Godfrey Hardy (Cranleigh, U.K., 1877–Cambridge 1947)
A mathematician, he taught at Oxford and Cambridge and made important contributions to the theory of numbers and mathematical analysis by studying

several types of series, in particular Fourier series. The author of more than three hundred scientific articles and some texts of pure mathematics, he was president of the London Mathematical Society and a member of the Royal Society. He received various honors, including the De Morgan, Sylvester, and Copley medals. He enjoyed notable success as a writer with *A Mathematician's Apology* (1940).

Stephen Hawking (Oxford, U.K., 1942–)
A theoretical physicist, he holds the chair previously occupied by Newton as Lucasian Professor in Cambridge. He has made important contributions to the knowledge and theoretical placing of black holes and tackled various cosmological problems. While still a student he was diagnosed with a disease that slowly weakened all the muscles of his body and now confines him to a wheelchair, permanently connected to a computer to communicate; this has not prevented him from rising through all the stages of a scientific career, and continuing an intense activity of research, teaching, and popularization. He is the author of the bestseller *A Brief History of Time: From the Big Bang to Black Holes* (1988).

Werner Heisenberg (Würzburg, Germany, 1901–Munich 1976)
A pupil of Arnold Somerfeld, assistant to Max Born in Göttingen and Niels Bohr in Copenhagen, from 1928 he taught theoretical physics at the University of Leipzig. He is one of the founders of quantum mechanics, having created so-called matrix mechanics (1925) and above all enunciating the principle of indeterminacy (1927), which bears his name. He received the Nobel Prize for physics in 1932; much concerned with the philosophical implications of twentieth-century physics, he wrote numerous nonspecialist works, including *Physics and Philosophy: The Revolution in Modern Science* (1959), *The Physicist's Conception of Nature* (1962), *Across the Frontiers* (1971), and *Tradition and Science* (1982, posthumous).

Hermann von Helmholtz (Potsdam, Germany, 1821—Berlin 1894)
He was a physiologist, physicist, and mathematician but also had a profound knowledge of philosophy, music, and art, and was considered the last great scientist capable of moving in every field of knowledge. He gave the most general formulation of the principle of the conservation of energy and established the irreversibility in transformations of energy, anticipating the concept of entropy. In the study of acoustics he invented an instrument (Helmholtz's resonator)

that makes it possible to determine the harmonic components of sounds. He also developed the thermodynamics of chemical processes. He exercised an enormous influence on nineteenth-century German science through research, teaching, and popularization and as a respected counselor of politicians and entrepreneurs.

William Herschel (Hanover, Germany, 1738–Slough, U.K., 1822)
Friedrich Wilhelm, later Sir William, is the most famous of the Herschels, a family of British astronomers of German origin. Like his father, William was also a musician and in 1757 moved to England. Together with his sister Caroline, who later joined him there, in 1781 he discovered the planet Uranus. This brought him great notoriety, and the following year he was called as an astronomer to the court of George III. Over the next thirty years he constructed various big telescopes and made important pioneering observations; in particular, he extended Charles Messier's catalogue of one hundred nebulae to comprise more than two thousand objects. He also discovered two satellites of Uranus (Titania and Oberon) and two of Saturn (Mimas and Enceladus). He was knighted in 1816. His son John, born in 1792, continued his father's work.

Douglas Hofstadter (New York 1945–)
After gaining his PhD in physics, he studied artificial intelligence. He taught at the University of Michigan and is currently a lecturer in computer science and cognitive sciences at the University of Indiana, Bloomington. Known for his qualities as a popularizer, in 1980 he won the Pulitzer Prize with the bestseller *Gödel, Escher, Bach: An Eternal Golden Braid*, which he himself defined as a "metaphorical fugue on minds and machines in the spirit of Lewis Carroll."

Fred Hoyle (Bingley, U.K., 1915–Bournemouth, U.K., 2001)
An astrophysicist and cosmologist, having made his contribution to the creation of radar, he studied the evolution of the stars and dealt with the great themes of cosmology. He is well known for having developed, with H. Bondi and T. Gold, the cosmological theory of the steady state, which provided "creation" with appropriate quantities of matter to compensate for the rarefaction caused by the expansion of the universe. The theory was superseded with the discovery of cosmic microwave background radiation, though Hoyle tried to reformulate it several times. He published various popular books and the successful science-fiction novel *The Black Cloud* (1959).

Edwin Hubble (Marshfield, Missouri, 1889–San Marino, California, 1953)
An astronomer at Mount Wilson Observatory, he discovered the existence of galaxies with a structure similar to that of the Milky Way, located outside it, and gave them a morphological classification. He measured the red shift in the spectra of stellar emission, obtaining first evidence of the expansion of the universe; in 1929 he arrived at the famous law (which bears his name) indicating a linear relation between red shift and the distance of the galaxies. The constant of proportionality that appears in the law ("Hubble's constant") is a fundamental parameter for cosmology, now an object of accurate measurements. The first NASA space telescope is named after him.

John Iliopoulos (Kalamata, Greece, 1940–)
A physicist, he gained his PhD at the École Normale Supérieure of Paris. In 1970, in collaboration with Sheldon Glashow and Luiciano Maiani, he recognized the importance of the fourth quark called charm; in 1974 he proposed the synthetic view of particle physics defined as the standard model. Together with Maiani he won the J. J. Sakurai Prize for particle physics in 1987.

Leopold Infeld (Krakow, Poland, 1898–Warsaw 1968)
A theoretical physicist, he collaborated with Max Born in the construction of a nonlinear electrodynamics. After moving to the United States, in Princeton he worked with Einstein and B. Hoffmann to develop a method that made it possible to derive, in general relativity, equations of motion from those of field. His book *The Evolution of Physics*, written in collaboration with Einstein, which surveys the history of modern physics in clear and succinct language, is famous. In 1950 he returned to Poland to head the Institute of Theoretical Physics in Warsaw.

Karl Jansky (Norman, Oklahoma, 1905–Red Bank, New Jersey, 1950)
An engineer, at the age of twenty-six, while working at Bell Laboratories, by chance he made the fundamental and historic discovery that celestial bodies can emit radio waves as well as light waves. Initially his results received little attention, but after the Second World War the importance of his instruments began largely to be appreciated, contributing to the affirmation of a new branch of astrophysics, radio astronomy. In his honor the name Jansky has been given to the unit of measure of radio flux (equal to 10^{-26} W/m^2 Hz).

Robert Jastrow (New York 1925–Arlington, Virginia, 2008)
A physicist, astronomer, and geologist, he taught at Columbia University and at Dartmouth College. He was the founder of the NASA Goddard Institute for Space Research and was one of the key figures from the beginning of the American space program; he was president of the NASA commission for lunar exploration. His qualities as a popularizer were revealed in books such as *Red Giants and White Dwarfs* (1967), *Until the Sun Dies* (1977), and *God and the Astronomers* (1978).

Edward Jenner (Berkeley, U.K., 1749–Berkeley 1823)
A physician and a pupil of John Hunter, he spent his working life at Berkeley. In 1796 he inoculated a boy of eight years old with material from cowpox blisters on the hand of a milkmaid; the experiment was successful and led to the introduction of smallpox vaccination. First much contested, the practice extended throughout the world and contributed toward fighting against smallpox, the first infectious disease to be defeated.

Pascual Jordan (Hanover, Germany, 1902–Hamburg 1980)
A theoretical physicist, he worked with Heisenberg and Born, to develop, in parallel with Dirac, a second quantum theory. He is considered the main founder of quantum field theory. He taught theoretical physics at the University of Hamburg from 1947 to 1971. He was awarded the Max Planck Medal (1942) and the Gauss Medal (1955).

Johannes Kepler (Weil, Germany, 1571–Ratisbon, Germany, 1630)
Initially engaged in ecclesiastical studies, he abandoned them to dedicate himself to astronomy. He worked at Prague for three years with the Danish astronomer Tycho Brahe, through whom he achieved the post of imperial astronomer. On the basis of Tycho's extremely accurate observations and within a heliocentric view, he formulated the famous three laws relative to planetary motion (which bear his name): in them the idea was advanced for the first time that the planets follow elliptical and not circular orbits, and the premises were established for the development of a planetary dynamic. This was then developed by Newton. In the introduction to his *Astronomia Nova* (1609) Kepler wrote that the Copernican theory was not in conflict with the Bible, since the latter had not been written with the aim of being an up-to-date tract of astronomy. In his *Harmonices Mundi* (1619), a wide-ranging astronomical work, Kepler believed

that he had identified in the musical harmony of the celestial spheres the profound reason of planetary dynamics.

Pierre-Simon Laplace (Beaumont-en-Auge, France, 1749–Paris 1827)
A mathematician, physicist, and astronomer, he was briefly Napoleon's minister of the interior and a member of the commission that defined the decimal metric system. He was author of a *Treatise on Celestial Mechanics* and was among the founders of the classical theory of probability as applied to natural phenomena; he established the laws of adiabatic transformation and with Lavoisier made the first measurements of specific heat. In his *Exposition of the System of the World* (1796), he wrote for a nonspecialist public, developing formally Kant's hypothesis on the origin of the solar system. In mathematics he contributed to the development of infinitesimal and algebraic analysis and introduced new instruments known as the Laplacian differential operator and Laplace transform.

Pierre Lecomte du Noüy (Paris 1883–Paris 1947)
He graduated in law and philosophy, but after meeting Alexis Carrel decided to embark on a scientific career and graduated in science at the Sorbonne. The lively interest of his researches into physics and chemistry applied to biology procured him a post at the Rockefeller Institute in New York, where he devoted himself to the study of blood and the problems of immunology. On his return to Paris, he headed the biophysical service of the Institut Pasteur and the École des Hautes-Études of the Sorbonne. His numerous philosophical and epistemological works, including *L'Avenir de l'Esprit* (1941), present a view of scientific knowledge and the phenomenon of evolution opposed to the dominant materialistic approach.

Jérôme Lejeune (Montrouge-sur-Seine, France, 1926–Châlons-sur-Marne, France, 1994)
Having graduated in medicine, he became a researcher at the Centre Nationale de la Recherche Scientifique while working in various hospitals in Paris. In 1957, with R. Turpino and M. Gautier, he discovered the anomaly defined as trisomia 21: for the first time this established a link between a state of mental weakness and a chromosomic aberration. In 1965 he became director of the genetic services of the Hôpital des Enfants Malades, and in 1968 head of the Institut de Progenèse. In 1974 he became a member of the Pontifical Academy

of Sciences, and in 1994 was nominated first president of the Pontifical Academy for Life. He was awarded numerous prizes, including the Prix Kennedy (1962), the William Allen Memorial Award (1969), and the Prix Griffuel (1993).

Georges Lemaître (Charleroi, Belgium, 1894–Louvain, Belgium, 1966)
An astrophysicist and cosmologist, he was ordained a priest in 1923. He continued his scientific activity as a researcher and teacher and taught mechanics and mathematical methods at the University of Louvain. His solution of Einstein's equations was an important reference point for the argument for the expansion of the universe. In 1933 he formulated the hypothesis of the birth of the universe from a "primordial atom," a hypothesis that constituted a first schematic version of that of the big bang. From 1960 to 1986 he was president of the Pontifical Academy of Sciences.

Leonardo da Vinci (Vinci, Italy, 1452–Amboise, France, 1519)
Trained in the environment of a country workshop, outside the schools and universities of the time, he developed a genius and creativity such as to make extraordinary contributions not only in the artistic field but also in physics, biology, and engineering. He was convinced that painting, and the arts in general, had to be based on a profound understanding of natural reality and its laws, which he also investigated by virtue of his great capacity for observation. Of his fertile production more than five thousand pages survive, in unmistakable mirror writing, and collected in ten codices preserved in various museums of the world.

Primo Levi (Turin, Italy, 1919–Turin 1987)
After graduating in chemistry, he worked in research and development in important chemical industries. He was imprisoned in a Nazi camp and bore witness to this in his *If This Is a Man* (1947) and *The Truce* (1963). He won the Strega (1979), Viareggia, and Campiello prizes (1972) and showed his literary ability in numerous other works, some of them with a scientific basis such as *The Sixth Day and Other Tales* (1967), *The Periodic Table* (1975), and his dialogue with the physicist Tullio Rege (1984).

Mario Livio (Bucharest, Romania, 1945–)
After completing his study of physics and mathematics in Israel, he taught physics at the Technion-Israel Institute of Technology until 1991. He was then

able to fulfill his passion for astrophysics by moving to the Scientific Institute of the Hubble Space Telescope at Baltimore, Maryland, where he studied the formation of black holes, the cosmological role of supernovae, and the formation of the planets. He is the author of *The Accelerating Universe* (2000), which brings out the "beauty" of the fundamental theories that describe the universe.

Konrad Lorenz (Vienna 1903–Altenberg, Austria, 1989)
A zoologist and founder of ethology, in his researches into animal behavior he distinguished an innate genetic base on which specific "evocative" instincts of individual forms of behavior with a hierarchical order act; he developed the concept of imprinting, by which the young of certain species learn their own specific characteristics and condition their subsequent behavior, coming into contact with their parents or with other individuals of the species. In 1973 he won the Nobel Prize for medicine (with K. von Frisch and N. Tinbergen). His books, also known to a wider public, include *King Solomon's Ring* (1949), *Man Meets Dog* (1950), *Evolution and Modification of Behaviour* (1963), and *Behind the Mirror* (1973).

Luciano Maiani (San Marino 1941–)
A theoretical physicist, he worked for many years at the Lyman Laboratory of Harvard University, where in 1970, in collaboration with Sheldon Glashow and John Iliopoulos, he proposed a broadening of the scheme of classification of quarks with the addition of the charm quark, the evidence for which was subsequently established by experiment. He is professor of theoretical physics at the La Sapienza University, Rome, and has been president of the Italian National Institute of Nuclear Physics. In 1997 he was appointed director general of CERN in Geneva.

Henry Margenau (Bielefeld, Germany, 1901–Hamden, Connecticut, 1998)
A physicist who gained his doctorate at the University of Nebraska, he spent his whole career at Yale University, where he taught physics and natural philosophy. He made significant contributions in electroscopy and was involved in a fundamental study of intermolecular and intranuclear forces. He published numerous books on the philosophy of science and was consultant for the scientific columns of *Time-Life*. His books include *The Nature of Physical Reality* (1977), *Einstein's Space and Van Gogh's Sky* (1982, with Lawrence Leshan), and *The Miracle of Existence* (1984).

James Clerk Maxwell (Edinburgh 1831–Cambridge 1879)
He was one of the major physicists and mathematicians of the nineteenth century. During the years he spent as a teacher at King's College, London, he published his main works on the theory of colors, the kinetic theory of gas, and the dynamic theory of the electromagnetic field. Forced to abandon teaching for reasons of health, he retired to his villa of Glenlair, where he completed his kinetic theory of gas and wrote his *Treatise on Electricity and Magnetism* (1873), a basic work that contains a complete development of the theory of light and the electromagnetic field, with the equations that bear his name. It was not particularly successful during his lifetime, and his theory was fully validated only when Hertz verified by experimentation the existence of electromagnetic waves. A complex personality and a rich human being, he developed profound reflections on the basic foundations of physics.

Barbara McClintock (Hartford, Connecticut, 1902–Huntington, New York, 1992)
A biologist, at the Carnegie Institute of Washington she began to study the unstable mutations in wheat: these researches led her to the discovery of transposable elements (transposomes) at a time when the structure of the double helix of DNA had not yet been discovered. Only later did the biological and medical significance of her discovery become clear. Subsequently, genetic instability was also found in micro-organisms, plants, animals, and human beings. Among other international honors she won the Nobel Prize for medicine in 1983.

Peter B. Medawar (Rio de Janeiro 1915–London 1987)
A British biologist, his study of skin transplants led him to discover immune tolerance acquired actively and gave impetus to research into the immunology of transplants. In 1960 he won the Nobel Prize for medicine and physiology together with F. Macfarlane Burnet and G. von Békésy. He has published various works with a methodological and popular character, such as *The Uniqueness of the Individual* (1969) and *Induction and Intuition in Scientific Thought* (1970).

Enrico Medi (Porto Recanati, Italy, 1911–Rome 1974)
He gained a doctorate at the age of twenty-one with Enrico Fermi, taught in the Universities of Palermo and Rome and was director of the Italian National Institute of Physics and vice president of Euratom. His studies on

the ionizing zones of the high atmosphere anticipated by five years the discovery by the American Van Allen. He played an important role in the popularization of science with brilliant television interviews among which was a direct conversation with the astronaut Neil Armstrong from the lunar spaceship. In 1996 the process for his beatification was begun.

Gregor Mendel (Heinzendorf, Silesia, 1822–Brno, Moravia, 1884)
He was a botanist, meteorologist, and geneticist. An Augustinian monk, in 1868 he became abbot of the monastery of Brno, which he had entered in 1843 and where for eight years he had carried out his famous experiments on hybridization, examining more than thirty thousand plants. The result of his researches, including the laws of heredity that bear his name, form the basis of classical genetics; however, they were ignored by the botanists of the time and rediscovered thirty years later by H. de Vries, C. F. Correns, and E. R. Tschermak von Seysenegg.

Robert Millikan (Morrison, Illinois, 1868–Pasadena, California, 1953)
A physicist, pupil of A. A. Michelson, in 1911 he carried out the famous experiment with which he demonstrated the existence of the elementary electrical charge, the value of which he determined. He turned his researches to cosmic rays and the charges in gases; in 1916, by studying the photoelectrical effect he determined the value of Planck's constant. In 1923 he won the Nobel Prize for physics.

Maria Mitchell (Nantucket, Massachusetts, 1818–Lynn, Massachusetts, 1889)
An astronomer, the first woman to be recognized as such in the United States, she was also the first woman to discover a comet, in 1847, and to join the American Academy of Arts and Sciences (in 1848) and the American Association for the Advancement of Science (in 1850). She taught astronomy at Vassar College until a year before her death.

Jacques Monod (Paris 1910–Cannes 1976)
A biochemist, in 1965 he shared the Nobel Prize for medicine and physiology with André Wolff and François Jacob for studies of the genetic control of the synthesis of enzymes in bacteria. In 1961, Monod and Jacob had verified the existence of the RNA messenger and subsequently proposed the concept of the operon, a group of genes that regulate the behavior of other genes. In

1970 he published the famous *Chance and Necessity*, a philosophical work that soon became a world bestseller and a point of reference in the debate on the origin of living beings. From 1971 he was director of the famous Insititut Pasteur in Paris.

Isaac Newton (Woolsthorpe, U.K., 1642–London 1727)
A mathematician and physicist, he is one of the fathers of modern science. His studies of mathematics, mechanics, optics, and astronomy are the basis of the respective disciplines, and his *Mathematical Principles of Natural Philosophy*, published in 1687, is one of the greatest scientific works of all time. He became the most famous and authoritative scientist in Europe at the beginning of the eighteenth century; he was Lucasian Professor of Mathematics in Cambridge and was elected president of the Royal Society. He was also actively occupied with alchemy and theology.

Hans Christian Oersted (Rudkjobing, Denmark, 1777–Copenhagen 1851)
A physicist and chemist, in a famous experiment carried out in 1820 at the University of Copenhagen, he observed that a magnetic needle near to a conductor carrying current, when rotated, tended to position itself perpendicularly to the conductor. This effect, the theory of which was then developed by Faraday, underlies the concept of the field and all electromagnetism.

J. Robert Oppenheimer (New York 1904–Princeton, New Jersey, 1967)
He researched in the field of quantum physics, first in Europe (where he collaborated with Max Born), then at Caltech and the University of Berkeley. He was also engaged in relativistic astrophysics, developing the first steps in the theory of black holes. In 1943 he was entrusted with directing the secret Los Alamos project, which gave rise to the atomic bombs dropped on Hiroshima and Nagasaki. He gave advice on the construction of the H bomb. In 1947 he became director of the Institute for Advanced Studies at Princeton. In a security hearing during the 1950s he was deemed to be a security risk and his security clearance was withdrawn; he was later reinstituted by President John F. Kennedy and awarded the Fermi Medal.

Blaise Pascal (Clermont-Ferrand, France, 1623–Paris 1662)
A philosopher, mathematician, and physicist, at the age of sixteen he formulated one of the fundamental theorems of projective geometry and at eighteen

constructed the first calculating machine. His scientific contributions include the law that bears his name, relating to the pressure of fluids, researches in infinitesimal calculus, and the development along with Fermat of the theory of probability. His philosophical thought expressed in the *Pensées* subordinates *l'esprit de géométrie* (scientific reason) to *l'esprit de finesse* (sentiment, intuition), which alone can cope with the contradictory nature of human experience and comprehend reality.

Louis Pasteur (Dole, France, 1822–Villeneuve l'Étang, France, 1895)
A biologist, he is known for his studies on fermentation and for the development of a theory of immunity. In 1875 he demonstrated the biological origin of micro-organisms and introduced the process of "pasteurization." He graduated in 1847 and in 1857 became scientific director at the École Normale of Paris. In 1864 he received a prize from the Académie Française for the study of spontaneous generation. From 1867 he taught chemistry at the Sorbonne and in 1881 was elected to the Académie.

Max Perutz (Vienna 1914–Cambridge 2002)
A biochemist, he began his work at the Cavendish Laboratory in Cambridge, where from 1962 he directed the Medical Research Council Laboratory of Molecular Biology. Working with the objective of building a bridge between biology and physics, he contributed to identifying the structure of hemoglobin by the diffraction of X-rays. In 1962 he was awarded the Nobel Prize for chemistry along with John C. Kendrew. He was a member of the Royal Society and an honorary member of the American Academy of Arts and Sciences.

Max Planck (Kiel, Germany, 1858–Göttingen, Germany, 1947)
A physicist, after studying in Munich and Berlin he became professor of physics at the University of Kiel and from 1889 to 1928 taught and researched without interruption in the University of Berlin. He is considered the father of quantum physics; in 1900, during research into the radiation of black bodies, he advanced the hypothesis that energy is irradiated in discrete quantities that he called quanta and formulated a law that links the energy of a single quantum proportionately to the frequency of the radiation, according to a universal constant known as Planck's constant. The value of his hypothesis was brought out by Einstein's work on the photoelectric effect and the development of atomic theory. In 1918 he was awarded the Nobel Prize for physics, and in 1930 he was

elected president of the Kaiser Wilhelm Institute, the main association of German scientists, which later was renamed the Max Planck Institute. Planck was expelled from the Institute for having openly criticized the Nazi regime, but resumed its direction at the end of the Second World War.

Henri Poincaré (Nancy, France, 1854–Paris 1912)
A mathematician and physicist, he quickly revealed his talent with the discovery of a new class of mathematical functions (which he called Fuchsian); subsequently he studied the functions of more variable complexes, algebraic topology, and differential equations and their applications in celestial mechanics. He made contributions to the study of the problem "of the three bodies" and laid the foundations on which the physics of chaotic systems is based. At the beginning of the twentieth century, he was actively interested in the innovations that were revolutionizing physics and deepened the epistemological aspects of the new sciences: his important works in this respect are *Science and Hypothesis* (1902), *The Value of Science* (1905), and *Science and Method* (1909).

John C. Polanyi (Berlin 1929–)
Of Hungarian origin (his father was the famous Michael, see below), he graduated and gained his PhD in Great Britain and then moved to Canada, where he became professor of chemistry at the University of Toronto. His research concentrated on the molecular movements of chemical reactions in gas and on surfaces, and in 1986 he was awarded the Nobel Prize for chemistry (with D. R. Hersbach and Yuan T. Lee) for research into the dynamics of elementary chemical processes. He is still occupied with the politics of science and the control of armaments; he founded the Canadian Pugwash Group and is coauthor of the volume *The Dangers of Nuclear War* (1979).

Michael Polanyi (Budapest, Hungary, 1891–Northampton, U.K. 1976)
He graduated in physics and medicine and gained a PhD in chemistry, and then studied the thermodynamics of absorption. From 1933 he was professor of chemistry at the University of Manchester. After the war his interests shifted to the history and philosophy of science; he developed a criticism of prevalent epistemological positions to the point of constructing an original personalist epistemology based on a unitary vision of human beings and an organic relation between faith and reason. His main works include *Personal Knowledge* (1958) and *Knowing and Being* (1969).

John Polkinghorne (Weston-super-Mare, U.K., 1930–)
A theoretical physicist, he was professor of applied physics at the University of Cambridge and worked with Gell-Mann on the first identification of the quark. When he became an Anglican priest, he dedicated himself to research into theology and is considered one of the greatest authorities on the relations between science and religion. He is president emeritus of Queens' College, Cambridge, and a fellow of the Royal Society. He has written a number of books, including *Science and Providence* (1989) and *Science and Christian Belief* (1994). In 2001 he was awarded the Templeton Prize.

Robert Pollack (New York 1940–)
A biologist, he was for a long time a collaborator with James Watson in research into the structure of DNA and taught biological sciences at Columbia University. A successful popularizer, he has won a Guggenheim Writing Fellowship and a Hamilton Medal. He is director of the Center for the Study of Science and Religion at Columbia University.

Ilya Prigogine (Moscow 1917–)
He left Russia in 1921 to follow the family to Belgium, where he graduated in chemistry and began to develop the theories that made him famous. Starting from the idea that the evolutionary tendency toward disorder postulated by the second principle of thermodynamics is not in fact inevitable, he deepened the concept of "dissipative structure," capable of surviving indefinitely in equilibrium with the environment. His researches into thermodynamics and the concepts of time and irreversibility gained him a long series of honors, culminating in 1977 with the Nobel Prize for chemistry. He has been director of the Instituts Internationaux Solvay de Physique et Chimie in Brussels and the Center for Studies in Statistical Mechanics named after him at the University of Texas at Austin. A keen supporter of the need for a dialogue between scientific culture and the humanities, Prigogine is the author of bestsellers such as *Order Out of Chaos* (1984, with Isabelle Stengers), *The End of Certainty* (1997, with Isabelle Stengers), and *Is Future Given?* (2003).

John W. S. Rayleigh (Langford Grove, U.K., 1842–Turling Place, U.K., 1919)
A physicist, he succeeded James C. Maxwell at the University of Cambridge. His studies were focused on acoustics, optics, and electromagnetic radiation; he gave an interpretation of the irradiation of black bodies that was incorporated

into Max Planck's more general theory. He was awarded the Nobel Prize for physics in 1904 for his extraordinarily precise measurements of the density of the atmosphere and its gaseous constituents, which led to the discovery of argon and other noble gases by W. Ramsey. In 1905 he was nominated president of the Royal Society.

Francesco Redi (Arezzo, Italy, 1626–Pisa 1697)
A physician with a great reputation and also a man of letters, he was a member of the Accademia del Cimento. His works became very important both for the results that he achieved in demolishing some Aristotelian theories by means of skillful experimental activity (spontaneous generation, the venom of vipers, etc.) and for his tenacious use of a technique of medicine clearly derived from Hippocrates and based on a rule of prevention depending on a balanced way of life and the use of exclusively natural remedies.

Hubert Reeves (Montreal, Canada, 1932–)
An astrophysicist, after gaining his PhD at Cornell University he taught at the University of Montreal, and, in 1965, having moved to France, became director of the Centre National de la Recherche Scientifique. He carried out research mainly in the field of nuclear astrophysics, specializing in the origin of light elements like helium, deuterium, and lithium. He received numerous honors and is well known as a popularizer: his books include *Atoms of Silence* (1985) and *Hour of Our Delight* (1990).

Wilhelm Conrad Röntgen (Lennep, Germany, 1845–Munich 1923)
A physicist, pupil of Rudolf Clausius, he studied specific heat and capillarity; he also studied conduction in rarefied gases, discovering X-rays, a large part of the characteristics of which he discovered without deciphering their nature. At any rate he used the penetrating power of X-rays, differing through various substances, to realize the first radiography; he did not patent his apparatus or seek any financial gain. He received the Nobel Prize for physics (1901) but gave the money to the University of Würzburg to finance scientific research.

Robert Rosen (Brooklyn, New York, 1934–Rochester, New York, 1998)
He worked on the frontiers of biology, physics, and chemistry and was a pioneer in theoretical biology. A pupil of the theoretical physicist and biologist

Nicholas Rashevsky, he was professor of biophysics and physiology in the faculty of medicine of Dalhousie University. He contributed to demonstrating that the Newtonian model of physics is inadequate for describing biological systems. His researches, rigorously described in his book *Life Itself* (1991), indicated how biology can provide important guidelines for a broader view of physics. He is the author of thirteen volumes on the foundations of measurement, seven volumes on advances in theoretical biology, and *Anticipatory Systems* (2003).

Bruno Rossi (Venice 1905–Boston, Massachusetts, 1993)
A physicist, he taught in Padua and in 1938 had to leave Italy, moving to the U.S. After some years of teaching at the University of Chicago and Cornell University, he took part in the Manhattan Project at Los Alamos. After the war he became professor of physics at MIT in Boston. His researches constitute a fundamental chapter in the study of cosmic rays.

Carlo Rubbia (Gorizia, Italy, 1934–)
He graduated in physics at the Scuola Normale Superiore di Pisa and carried out the first research into weak interactions at Columbia University. In 1970 he became professor of physics at Harvard and from 1989 to 1993 was director general of CERN in Geneva. Here he was engaged in intense scientific activity and in 1983 discovered the bosons W and Z^0, the quanta of weak interaction; he received the Nobel Prize for the discovery in 1984, together with Simon van der Meer. His researches in particle physics led to the identification of the quark top. He is currently president of ENEA.

Bertrand Russell (Ravenscroft, U.K., 1872–Ravenscroft 1970)
A mathematician and philosopher, he graduated at Trinity College, Cambridge, where he also began his teaching career. After 1900 he began to be concerned with the basis of logics and the problem of the foundation of mathematics, publishing *The Principles of Mathematics* (1903) and the monumental three volumes of *Principia Mathematica* (1910–13), written in collaboration with A. N. Whitehead. His pacifism and his sympathy for socialism were obstacles to his academic carreer, even leading to his imprisonment. After the Second World War, on his return to Cambridge, he published important works such as *A History of Western Philosophy* (1946) and *Human Knowledge: Its Scope and Limits* (1948). In 1950 he was awarded the Nobel Prize for Literature.

Ernest Rutherford (Brightwater, New Zealand, 1871–Cambridge 1937)
A physicist, he taught at the Universities of Cambridge, Montreal, and Manchester. In 1919 he became directory of the Cavendish Laboratory in Cambridge, which became a magnet for many researchers and scientists. Following his researches into radioactivity, he discovered the emission from radium of alpha and beta rays; in a famous experiment he discovered the existence of the nucleus of the atom and formulated a model of the atom in which the electrons rotate around a positive central nucleus; this was the first step toward successive atomic models based on quantum physics. In 1909 he won the Nobel Prize for chemistry. In 1931 he was elevated to the peerage and given the Order of Merit.

Oliver Sacks (London 1933–)
A physician, after graduating in London and specializing in neurology at Oxford, he moved to New York, where he dedicated himself to clinical work, being concerned above all with patients suffering from chronic emicrania and postencephalitic Parkinson's disease. In the course of his research, he advanced studies of the function of the right hemisphere and the repercussions on the central system of peripheral lesions and specific deficits. His clinical experiences, marked with an evident passion for people, form the basis of his books, many of which have become bestsellers: *The Man Who Mistook His Wife for a Hat* (1985), *An Anthropologist on Mars* (1995), and *Uncle Tungsten* (2001); his *Awakenings* (1973) was the subject of a film of the same name.

Igor R. Safarevič (Russia 1923–)
A world-famous mathematician, he is a corresponding member of the Russian Academy of Sciences. His researches have been directed mainly to the field of algebra and algebraic geometry. He has also written numerous nonscientific books, such as *Religious Legislation in the USSR* (1976) and *Socialism as a World Historical Phenomenon* (1980) (both in Russian). In 1996 he was given an honorary doctorate by the Sorbonne.

Carl Sagan (New York 1934–Seattle, Washington, 1996)
An astronomer and writer, he was one of the precursors of astrobiology. He taught astronomy and space sciences at Cornell University, where he directed the Laboratory of Planetary Studies. He played a leading role in planetary missions such as Mariner, Viking, and Voyager, for which he received recognition from NASA for his "Exceptional Scientific Achievement" and twice

for "Distinguished Public Service." At the end of the 1950s, his studies were mainly on planetology, the origin of life, and the evolution of the earth. His *Cosmos* was the best-selling scientific book in English of all time. Cofounder and president of the Planetary Society, he worked as visiting scientist at the Jet Propulsion Laboratory of Caltech. Among other honors he received the Pulitzer Prize and the Oersted Medal.

Allan Sandage (Iowa City, Iowa, 1926–)
An astrophysicist, while still a student he was assistant to the great astronomer Edwin Hubble and from 1952 was a member of the staff of Mount Wilson and Mount Palomar Observatories. With Martin Schwarzschild he determined the age of the globular masses, and with Gustav Tammann he contributed to the calibration of the "standard candle" necessary to measure the distance of the most remote galaxies. He many times proposed updated estimates of the value of the Hubble constant, the fundamental parameter for calculating the age of the universe. He has received numerous honors, including the Eddington Medal of the Royal Society, the U.S. National Medal of Science, the Pius XI Medal, and the Crafoord Prize of the Swedish Academy of Sciences.

Erwin Schrödinger (Vienna 1887–Vienna 1961)
A physicist, he was one of the founders of quantum mechanics. He taught physics at the Universities of Breslau, Zurich, and Berlin, where he succeeded Max Planck in the chair of theoretical physics until 1933, when he had to leave the capital because of his anti-Nazi positions. In 1939 he moved to Dublin, where he contributed to the birth of the Dublin Institute for Advanced Studies and remained there for seventeen years before returning to Vienna. The main part of his work consisted in studies relating to the foundation of quantum mechanics, for which he won the Nobel Prize for physics (together with Paul Dirac) in 1933. He also wrote many popular works that reveal interests beyond physics, in philosophy, epistemology, and the life sciences. His best-known books include *What Is Life?* (1947), *Science and Humanism* (1951), *Mind and Matter* (1956), and *My View of the World* (1961).

Francesco Severi (Arezzo, Italy, 1879–Rome 1961)
A mathematician, he taught in the Universities of Turin, Bologna, Pisa, Parma, Padua, and Rome, where he became rector in 1923. He developed the theory of algebraic varieties, linking Italian algebra to transcendental French and

German algebra. He received numerous honors, including the Gold Medal of the Society of the XL, the Borodin Prize of the Academy of Sciences of Paris, and the Royal Prize of the Accademia dei Lincei. In 1938 he founded the Italian National Institute of Higher Mathematics. His cultural and spiritual journey is related in his *Dalla scienza alla fede*, written after his conversion at the beginning of the 1950s.

Theobald Smith (Albany, New York, 1859–New York 1934)
A microbiologist and pathologist, having taught at Columbia University and Harvard, he became director of the department of animal pathology at the Rockefeller Institute in Princeton. His discovery in 1889 of the microbial causes and transmission mechanisms of bovine fever (*babesia bigemina*) opened up the way to the control of the disease, of yellow fever, and of other parasitical diseases. He was also the first to distinguish the bacillus of bovine tuberculosis from that of human tuberculosis, facilitating Robert Koch's work.

George Smoot (Yukon, Florida, 1945–)
He gained his PhD in physics and mathematics at MIT in 1970 with a study on the decay of subatomic particles. From then on, his research developed at the Lawrence Berkeley National Laboratory, initially on the study of antimatter. Today he is an authority in the field of cosmic microwave background radiation. He has directed various experiments from the earth and from stratospheric balloons to measure the cosmic background. From 1974 he has been one of the leaders of the NASA COBE (Cosmic Background Explorer) space project, launched in 1989, with the role of principal investigator of the DMR (Differential Microwave Radiometer) instrument, which for the first time had observed the slight lack of uniformity in the cosmic background, known as "anisotropy," opening up a new stage in cosmology.

Lazzaro Spallanzani (Scandiano, Italy, 1729–Pavia, Italy, 1799)
One of the most important naturalists of the eighteenth century, an experimental biologist and physicist, he was also engaged in astronomy and physics. A great observer and able experimenter, he studied the problem of spontaneous generation in the wake of Redi, obtaining notable experimental results above all at a microscopic level. Becoming professor of natural history at the University of Paris, he did research fundamental to the development of physiology, in particular the digestive and reproductive apparatus.

Nicolas Steno (Copenhagen 1638–Schwerin, Germany, 1686)
A Danish anatomist and geologist, he studied and described the brain, the lymphatic system, the circulatory system, and the reproductive organs; he discovered the way in which the parotid gland brings saliva to the oral cavity, known as Steno's duct. In geology he made observations on crystals, enunciating the law of the constancy of the dihedral angle. After going to the Universities of Amsterdam, Leiden, and Paris, he arrived in Pisa and during his stay in Italy converted to Catholicism, becoming a priest in 1675 and then bishop of a German diocese comprising Hamburg and Hanover. In 1946 he was recognized as a "servant of God" and in 1988 he was beatified by John Paul II.

Albert Szent-Györgi (Budapest, Hungary, 1893–Woods Hole, Massachusetts, 1986)
He graduated in medicine and after a PhD in chemistry at Cambridge, devoted himself to biochemistry, in particular studying muscular biochemistry, the processes of oxidation reduction, and the catalysis of fumaric acid. In 1928 he isolated a substance, hexuronic acid, later called ascorbic acid (Vitamin C). In 1937 he was awarded the Nobel Prize for medicine and physiology. After the Second World War, he was involved in the reconstruction of the Hungarian Academy of Sciences, but in 1947 for political reasons he moved to the United States.

Pierre Teilhard de Chardin (Sarcenal, France, 1881–New York 1955)
A paleontologist and geologist but also a philosopher and theologian, he entered the Society of Jesus in 1899 and pursued his scientific activity: he taught geology and paleontology in the Institut Catholique in Paris and took part in numerous expeditions in the East—in China, Burma, Java, and India—contributing to the discovery of so-called Peking Man, the fossil hominid who lived two hundred thousand to three hundred thousand years ago. In his attempt to reconcile the theory of evolution with Catholic doctrine, he developed a cosmic vision that sees the whole universe and humankind tending toward an omega point: the cosmic Christ. His system of thought has caused some perplexity on the theological level, and his most important books were published posthumously: these include *The Phenomenon of Man* (1959), *The Divine Milieu* (1956), and *The Future of Man* (1964).

René Thom (Montbéliard, France, 1923–Bures-sur-Yvette, France, 2002)
He graduated in mathematics at the École Normale Supérieure of Paris, taught in the Universities of Strasbourg and Grenoble, and, from 1963, at the Institute of Higher Scientific Studies in Bures-sur-Yvette. In 1958 he received the Fields Medal, the greatest international scientific award for mathematicians. He was one of the founders of differential topology and is known above all for the theory of catastrophes, an original attempt to apply mathematics to natural phenomena. In his view the world is not chaos and its objects are rational structures following one another according to laws that morphology must investigate. His works include *Structural Stability and Morphogenesis* (1980) and *Modèles mathématiques de la morphogenèse* (1985).

William Homan Thorpe (Hastings, U.K., 1902–Cambridgeshire 1986)
A biologist, he was director of the department of animal behavior in the zoological faculty at Cambridge University and fellow of Jesus College. He is considered a world authority in the field of ethology, in particular on the behavior of birds and the significance of their song as communication. His books include *Duetting and Antiphonal Song in Birds: Its Extent and Significance (*1972), *Origins and Rise of Ethology: The Science of the Natural Behaviour of Animals* (1979), and *Natural Science* (1986).

Campbell M. Wade
Senior researcher in radio astronomy at the National Radio Astronomy Observatory (NRAO) at the beginning of the 1970s, along with Robert Michael Hjellming he devoted himself to observations aimed at identifying stellar radio emissions, also using the Green Bank interferometer (GBI) in West Virginia. His pioneering work in these years contributed to the discovery of radio stars, novae, and X-ray sources. Subsequently he has devoted himself to observations with the Very Large Array (VLA).

Alfred Wallace (Usk, U.K., 1823–Broadstone, U.K., 1913)
After working as an engineer, geographer, and architect, following a meeting with Henry W. Bates he devoted himself entirely to the natural sciences. He took part in numerous scientific expeditions, in particular in Amazonia and Malaysia, making notable contributions in the fields of biogeography and entomology. He developed the idea of natural selection independently of Charles Darwin, differing from Darwin on various points.

Steven Weinberg (New York 1933–)
A physicist and cosmologist, he has taught at Columbia University, at Berkeley, MIT, Harvard, and finally the University of Texas at Austin. He was awarded the Nobel Prize in 1979 (together with Glashow and Salam) for his contributions to the theory of the unified weak and electromagnetic interaction between elementary particles. A member of numerous academies and institutions, he is also well-known as a popularizer; his famous *The First Three Minutes* (1977) has been translated into twenty-two languages.

Victor F. Weisskopf (Vienna 1908–Newton, Massachusetts, 2002)
A physicist, he graduated in Göttingen and moved to the United States in 1937. He then took part in the Manhattan Project at Los Alamos. In 1945 he became professor of physics at MIT. From 1961 to 1965 he was director of CERN in Geneva, and was a member of various international institutes and academies, receiving many scientific honors. His human stature and his cultural authority are witnessed to not least in his books *Knowledge and Wonder* (1979) and *The Privilege of Being a Physicist* (1989).

John Archibald Wheeler (Jacksonville, Florida, 1911– Hightstown, New Jersey, 2008)
A physicist, he worked in Copenhagen with Nils Bohr and in 1938 entered Princeton University, where he spent all his career apart from two periods devoted to military nuclear research in Chicago and Los Alamos. As well as original results in the physics of nuclear reactions, together with David Hill he developed a new model of the nucleus of the atom represented as resonance between a zone in rotation and one in vibration. His main contributions are on relativistic astrophysics and in particular the theory of black holes, to which he gave this definition at the beginning of the 1970s.

Alfred North Whitehead (Ramsgate, U.K., 1861–Cambridge, Massachusetts, 1947)
A mathematician and philosopher, he developed and carried out with Bertrand Russell the project of the *Principia Mathematica*. After teaching mathematics at Trinity College, Cambridge, University College, London, and the Imperial College of Science and Technology in Kensington, in 1924 he became professor of philosophy at Harvard. The originality of his thought was manifested in his conviction of the need for a metaphysics capable of integrating

science, religion, morals, and aesthetics. His reconstruction of the historical development of scientific thought in *Science and the Modern World* (1959) is also interesting.

Eugene Paul Wigner (Budapest, Hungary, 1902–Princeton, New Jersey, 1995)
A physicist and mathematician, after collaborating in the Manhattan Project at the University of Chicago, he developed his researches in the field of nuclear physics and taught at Princeton University until 1971. He was awarded the Nobel Prize for physics in 1963 for his studies on the application of group theory to atomic and nuclear physics. Other recognitions include the Enrico Fermi Prize, the Atom Prize for Peace, the Franklin Medal, and the Planck Medal of the German Society of Physics. He was president of the American Society of Physics and a member of the consultative committee of the U.S. Commission for Atomic Energy.

David T. Wilkinson (Hillsdale, Michigan, 1935–Princeton, New Jersey, 2002)
After gaining a PhD at the University of Michigan, he taught physics at Princeton University, of which he was chairman from 1987 to 1990. He was a pioneer in the study of the cosmic background of microwaves and the cosmic microwave background radiation of the big bang and in the 1970s was a member of Robert H. Dicke's group involved in the phases of the discovery of radiation. More recently he was among the initiators of the mission of the second-generation MAP (Microwave Anisotropy Probe), and then COBE, launched in June 2001. A passionate teacher, he received the Princeton President's Award for excellence in teaching. In 2001 he received the James Craig Watson Medal in recognition of his contribution to astronomy.

Lowell L. Wood
Senior researcher at the Lawrence Livermore National Laboratory in the United States, he has directed the program of advanced technology and the division for special studies of the physical sciences department. He has made contributions to the national security of the United States in the areas of energy, inertial confinement fusion, submarine communications, nuclear projects, and computational technologies. He is a member of the board of directors of the Hertz Foundation and the advisory committee for the X Prize for encouraging spatial tourism. In 1981 he was given the E. O. Lawrence Award.

Appendix B
Glossary

10^n, exponential notation

A typical way in which scientists express numbers that makes it easy to state very high and very low values by resorting to powers of 10; the exponent of 10 thus indicates the number of zeros and allows one to estimate the order of magnitude at a glance. A smaller number is written by resorting to a multiple of 10, for example: $34{,}800 = 3.48 \times 10{,}000 = 3.48 \times 10^4$. A very small number is written by resorting to division by a multiple of 10, e.g., $0.001289 = 1.289/1{,}000 = 1.289 \times 10^{-3}$.

Actinium

Actinium (symbol Ac, atomic number 89) is a metal that in normal conditions is poisonous, with a silvery white color, and glows in the dark. The most stable isotope (^{227}Ac) has a half-life of 21.6 years. It reacts with water, liberating gaseous hydrogen. Its name derives from the Greek *aktinos* (ray).

Alpha rays

These are particles formed of two protons and two neutrons, bound together by nuclear interactions. They constitute a very stable structure, and consist essentially of helium nuclei (^4He) completely ionized (without electrons). Because of their stability, alpha particles play an essential role in nucleosynthesis within the stars, through which the heavy elements, from carbon to iron, are produced. Alpha decay is a process in which a heavy nucleus emits an alpha particle, transforming itself into an atom with a mass number at least 4 lower, and an atomic number at least 2 lower.

Antimatter

A form of matter in which some key properties of individual particles appear in inverted form. For example, the antiparticle of the electron, called a positron, has an equal but opposite charge to that of the electron. Some particles with no charge have corresponding antiparticles. When a particle encounters its anti-particle, they annihilate, emitting a high-energy photon. In the first instants of its history, when the energy level was sufficiently high, the universe was filled with a mixture of particles and antiparticles. All the matter that we now observe and of which we are made is due to a small excess of matter over primordial antimatter. The antiparticles are found in cosmic rays and are ordinarily produced in high-energy physical laboratories. Today it is also possible to produce antiatoms of light elements.

Avogadro number

Lorenzo Romano Amedeo Carlo Avogadro (1776–1856), a count of Turin, formulated the law that takes its name from him as follows: "Equal volumes of all the gases at a high temperature and pressure contain the same number of molecules." Avogadro's number (or constant), equal to 6.022 x 1023, expresses the quantity of molecules present in a "mole" of gas weighing a number of grams equal to the atomic weight of the element.

Beta rays

These are essentially rapid electrons. They can be generated in so-called beta decay in which a neutron, isolated or within a nucleus, emits an electron (or beta ray) and an antineutrino, transforming itself into a proton. If such decay happens within an atomic nucleus, this will increase its electrical charge by a unit, transforming itself into a nucleus of a different element.

Black holes

Concentrations of matter associated with a gravitational field making space-time fold back completely on itself. The theory shows that for any mass m there is a critical radius (the so-called Schwarzschild radius) such that, if the mass m is contained within this radius, space-time shuts in on itself. This radius is equal to $2Gm/c^2$ where G is the constant of gravitation and c the velocity of light. The Schwarzschild radius of the sun is around 3 km, of the earth less than 1 cm. It is thought that final phases of the stars with a mass at least three times greater than that of the sun can normally lead to the formation of black holes. After the explosion in the form of a supernova, the residual nucleus continues to contract, producing an increasingly intense gravitational field (and thus a curvature of space-time). The object thus cannot be observed directly, but can be revealed by the presence of effects (e.g., emission of X-rays) on neighboring bodies, especially where a binary system is involved. Various objects are candidates for black holes, the best-known of which is the X-ray source Cygnus X-1. Recently, the presence of a supermassive black hole has been inferred in the center of our galaxy as well as of external galaxies.

Cosmic microwave background radiation
This is electromagnetic radiation released in the primordial universe and still observable today as a sea of low-energy photons (with wavelengths in the millimeter to centimeter range) that pervades the whole universe. George Gamov and collaborators in the 1940s predicted its existence, but the radiation was only discovered serendipitously in 1965 by Arno Prizias and Robert Wilson. Cosmic microwave background radiation makes it possible to obtain a direct image of the primordial universe when the universe was in its first infancy (fifty thousand times younger than today) before the formation of the galaxies and other cosmic structures. The observed details of the spectral distribution of the cosmic microwave background radiation, its slight deviation from uniformity, and its polarization coincide in a spectacular way with the predictions of the evolutionary cosmological scenario.

Cosmic rays
Particles coming from space, normally with an electric charge, that enter the terrestrial atmosphere at high energy. A single particle can have an energy of more than 10^{20} electrovolts, far superior to what can now be obtained with the most powerful particle accelerators. The cosmic rays of less energy originate in the sun; those with energies of 10^{9} to 10^{19} electrovolts come from sources in our galaxy, typically supernovae, while particles with even greater energy probably come from outside the galaxy.

Decay
A process in which a radioactive nucleus or an unstable particle or an atom is transformed into a lower-energy system emitting one or more particles or gamma rays.

DNA
Deoxyribonucleic acid. This is a molecule with large dimensions contained in the nucleus of the cell and made up of two filaments twining one around the other to form the structure of a double helix (discovered by James Watson and Francis Crick in 1953). Each filament results from the combination of molecules of simpler substances in the nucleotides that differ by virtue of the azotid bases that they contain. These bases are of four types—adenine, guanine, cytosine, and thymine—and their initials A, C, G, T are the four letters of the genetic code. The sequence in which these bases are arranged along the DNA filaments contains the instructions necessary for the biochemical activity of the cell and the hereditary characteristics of the resultant organisms.

Electromagnetic spectrum
Indicates the variety of wavelengths at which we find electromagnetic radiation, from long radio waves (with a wavelength of kilometers) to energetic gamma rays (with a wavelength of a billionth of a centimeter). Traditionally the electromagnetic spectrum is divided into various regions, dictated by historical and technical factors (the detectors used in the various regions use different technologies). These usually comprise the regions of radio, microwave, infrared, visible, ultraviolet, X-rays, and gamma rays.

Electromagnetism
Part of physics that studies electrical and magnetic phenomena and their reciprocal interactions. The laws that govern all electromagnetic phenomena have been synthesized in the four equations of the electromagnetic field formulated by James C. Maxwell.

Electrons
Particles with a negative electric charge that surround the nucleus of all atoms in a number equal to the number of protons present within the nucleus itself. Their mass is around two thousand times lower than that of the protons. They were discovered in 1897 by Joseph J. Thomson, and their charge was measured for the first time by Robert Millikan in 1911.

Electron volt (eV)
A unit of energy often used for elementary particles of electromagnetic radiation. It corresponds to the energy of an electron accelerated by a difference of

potential of 1 volt, and corresponds to 1.6 x 10^{-19} Joules. A thousand, a million, and a billion eV are denoted by KeV, MeV, and GeV, respectively.

Electroweak interactions

Together with the strong nuclear interactions and gravity, these comprise all the forces active in nature. The term "electroweak" derives from the unification of electromagnetic interactions (governed by Maxwell's equations) with the weak nuclear interactions that are responsible for radioactive decay. The unification proposed by Steven Weinberg and Abdul Salam in 1967 predicts that the interaction is mediated by so-called vector bosons, three of which (the fourth is the photon) were discovered at CERN in Geneva by Carlo Rubbia in 1983.

Enzymes

These are proteins that perform the function of biological catalysts. Enzymes regulate the rate of the biochemical reactions of cellular metabolisms. Their synthesis is directly controlled by DNA.

Gamma rays

Gamma rays are electromagnetic radiation with a wavelength in the range 10^{-10} to 10^{-14} meters, corresponding to energies between 10,000 electron volts (10 KeV) and 10 million electron volts (10 MeV) per photon. They are similar to X-rays but have a higher energy.

Genes

The whole of the DNA presented in a cell is called a genome: it is organized in chromosomes, which in turn are subdivided into small segments of genes, each of which controls the synthesis of a particular protein that intervenes in the formation of a hereditary characteristic.

Genetic code

The genetic code is the set of rules by which information encoded in genetic macro molecules (such as the DNA sequence) is translated into proteins (amino acid sequences) by living cells. The structure of DNA is substantially the same for all living beings.

Gluons

Particles with no mass that function as mediators of the forces that (like a glue) keep the quarks within the subatomic particles (protons, neutrons, and mesons) together. They form part of the family of bosons, and perform a function similar to that performed by photons in mediating electromagnetic force among electrically charged particles.

Ionization

The process of the production of ions—that is, of atoms that are not neutral but have a positive or negative charge following the cession or acquisition of electrons. There are molecules that ionize themselves spontaneously in solution. For example, chloridic acid in aqueous solution divides itself into hydrogen ions (positive) and chlorine ions (negative). Ionization can be provoked by collision with other particles or with a photon.

Kinetic energy

This is the energy that a body possesses as a consequence of its motion. Kinetic energy is proportional to the mass of the object and to the square of its velocity. Leptons are one of the two families of elementary particles of which matter is composed (the other is that of quarks). The family of leptons is constituted by six particles: the electron family, the muon, and the tauon, each with its respective neutrino.

Mutations

Alterations of genetic information after which the sequence of nucleotides is modified in the course of the replication of DNA: as a consequence the new DNA molecule is no longer an exact copy of the original and therefore can stimulate in the cell the synthesis of a different protein, with possible modifications of hereditary characteristics.

Neutrons

Particles with a zero electric charge and a mass similar to that of protons, to which they are connected within the atomic nuclei. Their existence was revealed in 1932 by Robert Chadwick. A free neutron is unstable and disintegrates, generating a proton, an electron, and a neutrino.

Neutron stars

Stars composed almost entirely of neutrons. These objects have an extraordinary density, very close to that of an atomic nucleus (a million billion times the density of water: 1 cm^3 of its matter would weigh 100 million tons). Today it is believed that neutron stars form at the end of the life of moderately massive stars, when their iron-nickel cores collapse, triggering a catastrophyc explosion of the star as supernova.

Non-Euclidean geometries
These are geometries based on the negation of Euclid's fifth postulate and which lead to curved space according to two possible situations. In hyperbolic geometry, introduced by János Bolyai and Nicolai Lobachevsky, space has a curvature similar to that of a saddle. Riemann's geometry, so-called elliptical geometry, is constructed on the surface of a sphere in which all the straight lines are represented by maximum circles: the curvature of space is spherical.

Photons
These are the elementary quanta of the electromagnetic field, particles with no mass that travel at the speed of light and present properties that are those of both corpuscles and of waves. All forms of electromagnetic radiation consist of photons, the energy of which is directly proportional (through Planck's constant) to the frequency of the associated wave. The existence of the photon was suggested by Albert Einstein in 1905 on the basis of experimental evidence from the photoelectric effect.

Polonium
A radioactive metallic element (symbol Po, atomic number 84) was discovered in 1898 by Marie Curie, who called it polonium in honour of her native land. It is one of the elements of the family of the radioactive decay of uranium-radium and is present in minerals containing radium. It is found in isotopes of a mass between 192 and 218. Polonium 210, so-called radium F, is the only isotope presented in nature and has a half-life of 138 days. Since many polonium isotopes disintegrate with the emission of alpha particles, the element is widely used in nuclear research.

Proteins
Organic substances with a high molecular weight and a very complex strong structure. They are formed from the combination of hundreds and even

thousands of molecules of twenty different amino-acids. They are present in all known forms of life, being the essential constituents of animal and vegetable cells, and control the diverse functions necessary for life.

Protons

Elementary particles with a positive charge that together with neutrons constitute the atomic nucleus. In every atom their number is equal to the number of electrons and is the characteristic of a particular chemical element. Protons are very stable particles, even if recent theories conjecture their decay over extremely long time scales.

Pulsar

A neutron star in rapid rotation emitting beams of radio waves that sweep space in an analogous way to the beam of a lighthouse. Our radio telescopes capture such waves in the form of periodical radio impulses of very great regularity and very high frequency. There are also pulsars that emit X-rays and gamma rays. The name "pulsar" is a contraction of pulsating radio source, a name chosen in analogy to quasar. Today many hundreds of pulsars are known, the majority of which have a period of the order of one second. The most rapid pulsar rotates on its spin axis at the fantastic rate of 625 rotations per second. Pulsars slow down slightly and constantly over time. The pulsar of the Crab Nebula, for example, slows down by a millionth of a second a day. The physics associated with these extreme conditions is an important test bed for the theory of relativity and for astrophysics.

Quantum

The term "quantum" is used to indicate the discretenature of physical quantities that in classical physics assume continuous values. For example, energy, momentum, and angular momentum are quantized. In particular, the quantum of action is indicated by the universal constant h, the so-called Planck constant, which makes it possible to quantize electromagnetic energy in "packets" equal to h multiplied by the frequency of the photon.

Quantum electrodynamics

This is the description that quantum theory gives of the behavior of electromagnetic radiation (including light) and of the interaction between charged particles through the exchange of photons. The theory has been verified with extreme precision by comparing predictions with the behavior of the electrons as observed in atoms. To the present day all the experimental tests made have confirmed the theory, and together with the theory of general relativity it can be considered one of the most solid theories of physics.

Quantum mechanics

This is the set of fundamental laws describing physical phenomena at the scale of atomic and subatomic particles. The beginnings of quantum mechanics go back to the start of the twentieth century. In 1900 Max Planck demonstrated that the nature of the radiation of a black body (i.e., a body capable of absorbing all the radiation that it receives) can be explained only on the supposition that radiation is emitted and absorbed by atoms in discrete quanta, indicating that there is a lower limit to the magnitude of the variations of energy in an atom. But it was Einstein to first establish that light could be considered in terms of particles; in 1905 he produced his findings on the photoelectric effect, for which he obtained the Nobel Prize. In 1927 Werner Heisenberg formulated his famous uncertainty principle showing the deep nature of the wave-particle duality. One of its versions establishes an absolute limit to our capacity to know simultaneously both the position and the degree of motion of a quantum system.

Quarks

These are elementary particles that constitute protons and neutrons (which are the building blocks of atomic nuclei), and other subatomic particles. Quarks are always found in nature as bound together to form composite particles, and are the only known particles whose electric charge takes on fractional values of the elementary charge. Quarks are of six different types (named "flavors"): "up," "down," "charm," "strange," "top," and "bottom." For every quark flavor there is a corresponding "antiquark," for which some of the properties have the opposite sign. The quark types with the lowest masses (the "up" and "down" quarks) are generally stable and are very common in the universe. The other four flavours are heavier and unstable.

Quasar

A nucleus of an active galaxy endowed with great energy. The name is an acronym of quasi-stellar radio source, linked to the first identifications made in radio frequencies (today we know that only one quasar out of two hundred is a strong radio source). In 1963 the radio source 3C 273 was hidden by the moon, and that made it possible to identify the source with an object of stellar appearance but at a distance comparable to that of the most remote galaxies. The rapid fluctuations of luminosity of such objects demonstrates that the radiation is emitted from very compact regions of about the dimension of the solar system or less. It is believed that the source of this extraordinary energy is a very massive black hole that swallows up material from the surrounding galaxies.

Radioactivity
Following the researches of Pierre and Marie Curie, scientists have identified different distinct types of particles that derive from radioactive processes. Three different types of radiation have been indicated with the first three letters of the Greek alphabet—alpha, beta, and gamma. These three forms of radiation can be separated by a magnetic field, given that alpha particles, with a positive charge, bend in one direction; beta particles, negative, in the opposite direction; and gamma rays, electrically neutral, do not bend at all.

Radio astronomy
This is that part of astrophysics concerning observations in the radio range of the electromagnetic spectrum—that is, at wavelengths typically between 10m and 1cm. Radio astronomy plays a key role in the investigation of the universe, particularly in the study of cosmic microwave background radiation, emissions of interstellar hydrogen (HI and HII regions), pulsars, radio galaxies, quasars, the remains of supernovae, identification of interstellar molecules, etc. The first radio signals of an astronomical origin were discovered by Karl Jansky in 1931.

Red shift
Light or any form of electromagnetic radiation coming from a moving source is received at a longer or shorter wavelength than that emitted, depending on whether the source is moving away from or toward the observer (the so-called Doppler effect). In this way it is possible to measure with remarkable precision the radial velocities of celestial objects (i.e., along the direction of view). Since red light has a greater wavelength than blue light, the term “red shift” is used when the source is moving away. The expansion of the universe produces a similar effect, so that distant galaxies show a systematic red shift from which it is possible to measure the rate of cosmic expansion.

Relativity, general theory of

This is the relativistic theory of gravity published by Einstein in 1915. The principal physical intuition on which general relativity is based is the so-called principle of equivalence, i.e., the assertion that the gravitational force as experienced locally while standing on a massive body is the same as the apparent force experienced by an observer in a *noninertial* (accelerated) frame of reference. From this Einstein concluded that gravity had to curve the space near a massive body: the presence of matter curves four-dimensional space-time. This curvature acts on everything within its surrounding environment, from the trajectory followed by light to the motion of other massive bodies. For moderate gravitational fields Einstein's theory coincides with the classical laws of Newtonian gravity, which becomes a particular case of it. Since gravity is the dominant force on large scales, the general theory of relativity also provides the basis of all modern cosmological models that seek to describe the evolution of the universe and its large-scale structure.

Relativity, special theory of

A theory that describes the dynamic relations between objects in uniform rectilinear motion, published by Albert Einstein in 1905. The main character of special relativity lies in the fact that space and time depend on the relative state of motion between the observer and the object observed. For example, for an observer at rest in his inertial system of reference, the time indicated by a clock in motion (with speed comparable to the speed of light) slows down and space shrinks in the direction of motion. This "relativization" of space and time is such as to maintain invariably a four-dimensional space-time element. The velocity of light is independent of the motion of the source and the observer, and is a universal constant. The famous relationship $E = mc^2$ between mass m and energy E (where c represents the speed of light) forms part of the theory of special relativity. All these forms of behavior have been proved experimentally with extraordinary precision.

Scintillations

Interplanetary scintillations are rapid variations (typically on time scales 0.1 to 10 seconds) in the apparent intensity of a compact astronomical radio source (such as a quasar) as its radio signal enters our local solar system and travels across interplanetary space. The rapid variations are produced by interference due to fluctuations in the density (and thus refractive index) of the solar wind, i.e., the supersonically expanding atmosphere of the sun, which fills interplanetary space. Nowadays interplanetary scintillations are still used to gain information on both the emitting astrophysical radio sources and on the characteristics (density, velocity) of the solar wind.

Spin

In quantum mechanics the electrons themselves have a degree of freedom in rotation. This indicates that the electron has a nonzero angular momentum (and therefore also a magnetic momentum) independent of its movement around the nucleus. Such an angular momentum is called spin. In practice we can imagine that the electron, as well as moving around the nucleus, also rotates on itself—just as the earth rotates on its own axis while rotating around the sun. In quantum mechanics the spin of a particle can assume only certain discrete values, and the values that it can assume depend on the type of particle. In the case of the electron, for example, the quantum numbers that specify the values that the spin can assume are just 1/2 or –1/2 (a single value in two opposite directions).

Standard model (particles)

This is the theory that sums up all current knowledge in the field of elementary particles and the forces that regulate their interactions. All the physical interactions observed in nature can be traced back to the study of the behavior of a limited number of elementary particles under the effect of four fundamental types of forces. Down to the nineteenth century only two of these interactions were known—electromagnetic and gravitational. The velocity of the propagation of these interactions, supposed by Newtonian physics to be infinite, is fixed by the theory of relativity with a value equal to the velocity of light in a vacuum. Successively the discovery of the neutron implied the consideration of strong nuclear interactions, responsible for the stability of nuclei. The decay of the neutron and the hypothesis of the neutrino led Enrico Fermi to introduce weak nuclear interactions, of less intensity than strong interactions, but superior to gravitational and electromagnetic interactions. In 1983 the Carlo Rubbia group discovered the bosons W and Z^0, the particles through which the weak interactions act. Physicists began to construct the standard model with the intention of reflecting all the interactions in a single comprehensive framework. The current standard model, while extremely powerful, still has significant limitations: it does not include the force of gravity; it does not explain the spectrum of the masses of the particles; different arbitrary parameters appear in it. To construct the model it is necessary to introduce Higgs's bosons, which the LHC particle accelerator at CERN may be able to detect in the near future.

Strong interactions

These are interactions occurring within atomic nuclei that, despite the repulsive action of the electrostatic forces, hold the protons and neutrons together in the atomic nuclei. The strong interaction has a very small radius of action, of the order of the dimensions of the nucleus itself.

Superconductivity

When certain materials are brought to very low temperatures, below the so-called transitional temperature, a drastic reduction of electrical resistance can be noted and very special magnetic properties appear. Many of the great physicists of the twentieth century, including Einstein, tested this, studying it experimentally and seeking both to explain its origin and to give a satisfactory theoretical explanation. Many potential applications are in use today in apparatuses such as diagnostic machines for nuclear magnetic resonance. The absence of significant electrical resistance can transport current with a low expenditure of energy, transfer intense currents in small-diameter wires, and easily produce very intense magnetic fields (a fact exploited among other things by trains with magnetic levitation, which can travel at 300 mph only a few inches above the ground). In pure metals and alloys the transition temperature is very low (around 265–250° below zero); but some composites containing copper, oxygen, and other less common elements (barium, strontium, lantanium) become superconductive at temperatures as high as 140° below zero, which can be obtained simply by immersing the material in liquid nitrogen.

Universal gravitation

This is the interaction between massive bodies that manifests itself as a reciprocal attraction. The classical law of universal gravitation, the grandiose conclusion introduced by Isaac Newton, asserts that the force between two masses is directly proportional to the product of their masses, and inversely proportional to the square of the reciprocal distance. This proportionality is fixed by the constant of gravitation G, measured for the first time by Henry Cavendish in 1798. The classical laws of celestial mechanics, and in particular Kepler's three laws, can be derived from Newton's laws. The force exercised on a body by the attraction of earth (the weight of the body) is a particular case (and a particularly familiar case) of the laws of universal gravity. Today the general theory of relativity has generalized and deepened Newton's law, which remains in accord with Einstein's laws in a first approximation.

Weak reactions
See "electroweak interactions."

White dwarfs
These are stars of comparable mass to that of the sun in the last phases of their evolution. When the reactions of nuclear fusion in the central regions of the star become less, the star loses its external envelops and the remaining high-density nucleus (mainly consituted by carbon and oxygen with a heavy iron core) is the white dwarfs. These stars have extremely reduced dimensions, typically comparable to that of a planet such as earth. They are therefore characterized by an enormous density, about a million times that of water.

Notes

Introduction

1. Euresis is an association for the promotion of science as an expression of the broader human quest for beauty and meaning (www.euresis.org).

Chapter 1—Wonder

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3. Denis Brian, *Einstein: A Life* (New York: John Wiley & Sons, 1996), 234.
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5. Immanuel Kant, *Universal Natural History and Theory of the Heavens,* trans. Stanley L. Jaki (Edinburgh: Scottish Academic Press, 1981), 108.
6. Archimedes, prologue to *The Sand Reckoner*.
7. Maria Mitchell, quoted in Mario Livio, *The Accelerating Universe: Infinite Expansion, the Cosmological Constant, and the Beauty of the Cosmos* (New York: John Wiley & Sons, 2000), 265.
8. Marie Curie, quoted in Ernst P. Fischer, *Aristotele, Einstein e gli altri* (Milan: Raffaello Cortina Editore, 1977), 270–71.
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10. Charles Darwin, *The Origin of Species*, vol. 2, World's Popular Classics (New York: Books, Inc., 1900), 438.
11. Hans Bethe, private correspondence with the author, quoted in Emilio Segrè, *Enrico Fermi, Physicist* (Chicago: University of Chicago Press, 1970), 59–60.
12. This is a fundamental equation of quantum mechanics, the solution to which allows us to determine the so-called wave function of a particle (or system of particles) and from this its principal properties in probabilistic terms.
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14. Federigo Enrìques, *Le matematiche nella storia e nella cultura* (Bologna: Zanichelli, 1982), 155–56.
15. Giorgio Cavallini, "Verbi del divenire e senso della meraviglia al Centro delle 'Esperienze intorno alla generazione spontanea degl'insetti' di Francesco Redi," in *Letteratura e scienza nella storia della cultura italiana* (Palermo: Panfredi, 1978), 538–46.
16. Eve Curie, *Madam Curie: A Biography*, trans. Vincent Sheean (Garden City, NY: Doubleday & Company, 1937), 373–75.

17. Sheldon Lee Glashow, “Le virtù della ricerca guidata dalla curisotià,” *KOS* 151:55.
18. Galileo Galilei, “The Assayer,” trans. Stilllman Drake, in *The Controversy on the Comets of 1618: Galileo Galilei, Horatio Grassi, Mario Guiducci, Johann Kepler*, trans. Stillman Drake and C. D. O’Malley (Philadelphia: University of Pennsylvania Press, 1960), 235–36.
19. Bruno Rossi, *Moments in the Life of a Scientist* (Cambridge: Cambridge University Press, 1990), 1, 3, 6.
20. An instrument that makes it possible to measure the quantity of ionizing radiation, or radiation capable of affecting electrons in a gas. The neutral gas is contained in an isolated chamber in which an electrical potential is maintained through two electrodes connected to an external circuit. When the radiation (typically photons) ionizes some gas molecules in the chamber, the charged particles are attracted by the electrodes, causing unforeseen falls in potential, which are revealed by the external circuit.
21. Anne Moreau Jansky Parsons, “Personal Recollections for the Green Bank Symposium,” in *Serendipitous Discoveries in Radio Astronomy: Proceedings of a Workshop Held at the National Radio Astronomy Observatory, Green Bank, West Virginia on May 4, 5, 6, 1983*, ed. K. Kellerman and B. Sheets (Green Bank, WV: National Radio Astronomy Observatory, 1983), 23.
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23. Albert Einstein, “On the Generalized Theory of Gravitation,” *Scientific American* 182, no. 4 (April 1950): 13–14.
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25. Max Planck, *Scientific Autobiography and Other Papers*, trans. Frank Gaynor (New York: Philosophical Library, 1949), 13.
26. John Archibald Wheeler, *A Journey into Gravity and Spacetime* (New York: American Scientific Library, 1990), xi.
27. Richard S. Westfall, *Never at Rest: A Biography of Isaac Newton* (Cambridge: Cambridge University Press, 1980), 863.
28. Leonardo da Vinci, *Scritti letterati* (Milan: Rizzoli, 1980), 184–85.

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4. William Herschel, “Construction of the Heavens,” quoted in Edward R. Harrison, *Cosmology: The Science of the Universe* (Cambridge: Cambridge University Press, 1981), 44.
5. Barbara McClintock, “Conversazione con l’Autore,” quoted in Ernst P. Fischer, *Aristotele, Einstein e gli altri* (Milan: Raffaello Cortina Editore, 1977), 309.
6. Peter Brian Medawar, *Induction and Intuition in Scientific Thought*, Jayne Lectures for 1968 (Philadelphia: American Philosophical Society, 1969), 42.
7. Luigi Giussani, *The Religious Sense*, trans. John Zucchi (Montreal and Kingston, Canada: McGill–Queens University Press, 1997).
8. Quoted in Jean Rostand, *Lazzaro Spallanzani e le origini della biologia sperimentali* (Turin: Einaudi, 1963), 31.
9. Medawar, *Induction and Intuition*, 54n44, 52n43.
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11. R. E. Billingham, L. Brent, and P. B. Medawar, “Quantitative Studies on Tissue Transplantation Immunity,” *Philosophical Transactions of the Royal Society*, B, 239 no. 666 (1956): 357–414.
12. Hubert Reeves, *Atoms of Silence: An Exploration of Cosmic Evolutio*n, trans. Ruth A. Lewis and John S. Lewis (Cambridge, MA: MIT Press, 1984), 30.
13. Robert Jastrow, *God and the Astronomers*, 2nd ed. (New York: W. W. Norton & Company, 1992), 18–21.

14. Arthur Eddington, *The Expanding Universe* (Cambridge: Cambridge University Press, 1933), 17, 3, 20–21.
15. Alexis Carrel, *Man, the Unknown* (New York: Harper & Brothers Publishers, 1939), 39–40.
16. Giussani, *Religious Sense*, 4.
17. Alexis Carrel, *Reflections on Life*, trans. from the French by Antonia White (New York: Hawthorn Books, 1952), 25, 26, 27–28.
18. Michael Faraday, *The Correspondence of Michael Faraday: Vol. 1, 1811–December 1831, Letters 1–524*, ed. Frank A. J. L. James (London: Institution of Electrical Engineers, 1991), 287–88, letter 179 (Faraday to André-Marie Ampère, September 3, 1822).
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21. G. H. Hardy, A *Mathematician's Apology* (Cambridge: Cambridge University Press, 1969), 122–24.
22. Timothy Ferris, *The Red Limit: The Search for the Edge of the Univers*e (New York: William Morrow and Company, 1977), 223.
23. Carl Sagan, "Introduction," in ibid., 13, 15–16.
24. Emilio Segrè, *From X-Rays to Quarks: Modern Physicists and Their Discoveries* (Berkeley: University of California Press, 1980), 178–79, 181, 182–84.
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4. Cf. Luigi Giussani, *The Religious Sense*, trans. John Zucchi (Montreal and Kingston, Canada: McGill–Queens University Press, 1997).
5. Michael Polanyi, "My Time with X-rays and Crystals, 1962," in *Knowing and Being: Essays by Michael Polanyi*, ed. Marjorie Grene (Chicago: University of Chicago Press, 1969), 100–101, 103–4.
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7. Quoted in Hubert Reeves, *Atoms of Silence: An Exploration of Cosmic Evolution*, trans. Ruth A. Lewis and John S. Lewis (Cambridge, MA: MIT Press, 1984), 37.
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9. Mikhail Bulgakov, *The Master and Margarita*, trans. Richard Pevear and Larissa Volokhonsky (New York: Penguin Books, 1997), 273.
10. Gell-Mann, *Quark and the Jaguar*, 75–76, 77–78.
11. Jean Rostand, *Lazzaro Spallanzani e le origini della biologia sperimentale* (Turin: Einaudi, 1963), 180–82.
12. W. I. B. Beveridge, *The Art of Scientific Investigation* (New York: Vintage Books, 1957), 138.
13. Francis Darwin, *Life and Letters of Charles Darwin* (London: John Murray, 1888); quoted in Beveridge, *Art of Scientific Investigation*, 138.
14. Hans Christian Oersted, quoted in G. Canguilhem, *Introduzione alla storia delle scienze* (Milan: Jaca Book, 1973), 389–90. Note that in the first part of the passage Oersted speaks of himself in the third person.
15. Quoted in Beveridge, *Art of Scientific Investigation*, 24.
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19. This is the fraction of neutrons absorbed in respect of the total neutrons directed toward the detector.
20. Beveridge, *Art of Scientific Investigation*, 36.
21. Primo Levi, *The Periodic Table* (London: Michael Joseph, 1985), 57–60.
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23. R. Hanbury Brown, "Observational Innovation and Radio Astronomy," in *Serendipitous Discoveries in Radio Astronomy: Proceedings of a Workshop Held at the National Radio Astronomy Observatory, Green Bank, West Virginia, on May 4, 5, 6, 1983*, ed. K. Kellerman and B. Sheets (Green Bank, WV: National Radio Astronomy Observatory, 1983), 211–12.

Chapter 4—Discovery

1. "Scintillations" are radio fluctuations registered by the instrument that in fact come from heavenly sources crossing the interplanetary medium, whereas "artificial interference" means disturbance of local origin (typically due to telecommunications), which can be confused with astronomical signals.
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6. Doroškevič and Novikov, who knew the work of Gamow and misinterpreted a statement in a Bell Lab report that contained an indication of the presence of cosmic microwave background radiation.
7. The Princeton group, led by Dicke, of which David Wilkinson was a member.
8. See Arno Penzias and Robert Wilson, who accidentally discovered cosmic microwave background radiation in 1964.
9. The reference here is to George Gamow, who with his students Alpher and Hermann made quantitative theoretical predictions of the presence of cosmic microwave background radiation in the 1940s.
10. These are the observations of interstellar cyanogen by Adams, Dunham, and McKeller from 1941, which already gave an indication of diffuse low temperature radiation; however, this indication was not understood and remained unknown until the 1965 discovery.
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15. Hermann von Helmholtz, quoted in W. I. B. Beveridge, *The Art of Scientific Investigation* (New York: Vintage Books, 1957), 81.
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17. Leo Esaki, "Preparare menti e cuori al XX secolo," in *Dall'informazione alla cultura, Dieci Nobel per il futuro* (Venice: Marsilio, 1956), 70–71.
18. Peter Brian Medawar, *Induction and Intuition in Scientific Thought*, Jayne Lectures for 1968 (Philadelphia: American Philosophical Society, 1969), 55–56, 58, 59.
19. Max F. Perutz, *Is Science Necessary? Essays on Science and Scientists* (New York: E. P. Dutton, 1989), 166–67.

20. Michael Polanyi, *The Tacit Dimension* (Garden City, NY: Doubleday & Company, 1966), 78–79.
21. John Polkinghorne, *Beyond Science: The Wider Human Context* (Cambridge: Cambridge University Press, 1996), 28–29.
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23. Enrico Fermi, *Collected Papers*, vol. 2 (Chicago: University of Chicago Press, 1965), 926–27.
24. Henri Poincaré, *Science and Meth*od, trans. Francis Maitland (n.p.: Dover Publications, 1952), 52–55.
25. These and other mathematical terms that follow (hypergeometric series, elliptical functions, Theta-Fuchsian functions) indicate some types of mathematical functions of particular importance; the discovery of their properties, due principally to Poincaré, gave impetus to new developments in modern mathematics. The Fuchsian functions were given their name by Poincaré himself, who began to study them on the basis of an article by Immanuel Fuchs on a particular differential equation with a rational coefficient.
26. Francesco Severi, *Dalla scienza alla fede* (Assisi: Edizioni Pro Civitate Christiana, 1959), 18–20.
27. Einstein, addressing a conference at the University of Kyoto, Japan, December 14, 1922, in Pais, "*Subtle Is the Lord . . .* ," 118–19, 139.
28. In 1887, Albert Michelson and Edward Morley performed a famous experiment in which they intended to prove the existence of ether, the hypothetical medium in which it was thought that light and other forms of electromagnetic radiation had to be propagated. The aim of the experiment, based on the principle of interference, was to demonstrate a difference between the speed of light coming from the direction of the earth's motion around the sun and that coming from a direction at right angles to it. The surprising result of the experiment was that the earth's motion did not affect the speed of light, which proved identical in both directions. This conclusion, confirmed by various successive experiments, is a fundamental experimental indication in support of the theory of relativity, in which the speed of light is one of the constants of nature. When Einstein developed the special theory of relativity in 1905, he was also inspired by Maxwell's equation, in which the speed of light appears as an absolute constant.
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31. Enrico Fermi, "The Nucleus," *Collected Papers* (Chicago: University of Chicago Press, 1965), paper no. 247, 834.
32. Sheldon Lee Glashow, "Le virtù della ricerca guidata dalla curiosità," *KOS* 151:53.
33. Ibid., 54.
34. C. M. Wade, "The Discovery of Radio Novae," in *Serendipitous Discoveries in Radio Astronomy*, 291–93.
35. See the introduction to this chapter.
36. Three degrees is an enormous degree of error for these measurements.
37. These are antennae that have a much broader response in one direction than in another.
38. This too is an enormous error.
39. Murray Gell-Mann, *The Quark and the Jaguar: Adventures in the Simple and the Complex* (New York: W. H. Freeman and Company, 1994), 262–64.
40. Often elementary particles are associated in groups in which different particles have around the same mass but different charges; this is the case with the proton-neutron pair. The isotopic spin is the quantity that describes mathematically the passage from proton to neutron (or vice versa). In reality the isotopic spin has nothing to do with the "spin" of elementary particles (which represents the angular element intrinsic to the particle). The term "isotopic spin" derives from the fact that the mathematical description of this quantity is very similar to that of the spin, and that the number of protons and neutrons determines the isotope that the atom represents.
41. Ronald Hare, *The Birth of Penicillin and the Disarming of Microbes* (London: George Allen and Unwin Ltd., 1970), 86–87.
42. Mario Livio, *The Accelerating Universe: Infinite Expansion, the Cosmological Constant, and the Beauty of the Cosmos* (New York: John Wiley & Sons, 2000), 219.
43. Quoted in W. I. B. Beveridge, *The Art of Scientific Investigation* (New York: Vintage Books, 1957).

44. Quoted in ibid., 192.
45. Ibid., 193.
46. Werner Heisenberg, *Physics and Beyond: Encounters and Conversations*, trans. Arnold J. Pomerans (New York: Harper Torchbooks, 1972), 61.
47. Johannes Kepler, "Prodromos dissertationum," in Ludovico Geymonat, *Galileo Galilei: A Biography and Inquiry into his Philosophy of Science* (New York: McGraw Hill, 1965).
48. Quoted in J. R. Baker, *The Scientific Life* (London: George Allen & Unwin Ltd., 1945), 155.
49. Rocky Kolb, *Blind Watchers of the Sky: The People and Ideas That Shaped Our View of the Universe* (Reading, MA: Helix Books, Addison-Wesley Publishing Company, 1996), 226–30.

Chapter 5–Certainty

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3. Vannevar Bush, "The Builders," in *Endless Horizons* (Washington, DC: Public Affairs Press, 1946), 179.
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cure as well as to kill. But there can be no doubt in what direction we must look to distinguish good from evil." John Paul II, "Science and Faith in the Search for Truth," address to teachers and university students in Cologne Cathedral, November 15, 1980, http://www.its.caltech.edu/~nmcenter/sci-cp/sci80111.html.

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