SPECIAL SECTION

Science, Reason and Passion

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ABSTRACT

The cultural atmosphere that presided at the origin of classical Western science is briefly discussed. One of the most characteristic features of Western science is the formulation of laws of nature, which lead to a deterministic description in which future and past play the same role. However, these characteristics, especially time reversibility, contradict everything we see around us. Everywhere we see the arrow of time. The recent developments in nonequilibrium physics and in the dynamics of unstable systems lead to a new concept of laws of nature no more associated with "certitudes" as with "probabilities." This formulation includes the arrow of time and describes an open, evolutionary universe, overcoming the Cartesian duality that puts Humans outside Nature.

The role played by passion and, more generally, irrational elements in processing knowledge is a subject of major interest, and one so immense that I can hope only to scratch the surface in discussing some of the aspects with which I am most familiar.

At first blush, we seem to be dealing here with a paradox. Isn't science by definition beyond passion, beyond even the pressing needs of society? This is what Einstein thought—he hoped scientists could get jobs as lighthouse-keepers. One can hardly help wondering how creative these lighthouse-keepers would be in the long run: I fear that after a few years, they would sink into solipsism and pointless wrangling.

Science is the expression of a culture. Its boundaries are hard to define. In the nineteenth century, Faraday preferred to be known as a "natural philosopher" rather than a "scientist." Indeed, the word "science" was not used in its present meaning until the seventeenth century. At any rate, it refers to a dialogue with nature. But nature is not a given; it implies a construction in which we take part. I have always liked what Heisenberg reports Niels Bohr said during a visit to Krönberg Castle in Denmark:

> Isn't it odd how this castle seems completely different when we think of it as the place where Hamlet lived? As scientists, we believe a castle is made of stones, and we admire the way the architect assembled them. The walls, the verdigris roof, the church beams—these make up the castle. Nothing should change just because Hamlet lived here, yet that changes everything. Suddenly the walls and the ramparts speak a totally different language. Still all we really know about Hamlet is that his name appears in a thirteenth-century chronicle. But everybody knows the questions Shakespeare had him ask, and the human depth they reveal; he too had to have a place in the world, here in Krönberg. . . .

How can one fail to recognize in Bohr's meditations here the leitmotif of his life as a scientist: the inseparability of the question of reality and the riddle of human existence? What is the castle of Krönberg, independent of the questions we put to it? The stones can speak to us of their molecules, the geological strata they were quarried from, perhaps of the extinct species they contain in fossil form, of the cultural influences that worked on the architect, or the questions that pursued Hamlet to his death. None of these matters are arbitrary, nor do they permit us to sidestep reference to Hamlet, whose presence here gives them meaning. Bohr's reflections very clearly show his assumption that the questions of the reality of nature and of human existence are inseparable. How can one be indifferent to problems that involve our existence? How can one not see them simultaneously with the eye of reason and the eye of passion?

People often wonder why science was born in Western Europe instead of China, a country that contributed so much to the development of our experimental discoveries. This is the question Joseph Needham posed so forcefully. The sixteenth- and seventeenth-century founders of Western science must surely have had unsurpassed enthusiasm and faith. The Florentine architect and humanist Leon Battista Alberti claimed that "Men can do all things, if they will." This motto applies to the great men of the Renaissance: Leonardo, Kepler, Galileo, Bacon. The very titles of Kepler's major works show how completely they are the expression of a magical view of the world: *The Cosmic Mystery, Celestial Physics, The Harmonies of the World.* Mystery, physics, harmony—what an odd trio for one of the great founders of modern science. How can men do "all things," as Alberti has it? Francis Bacon has the answer: men can do all things provided they obey the laws of nature. But obeying the laws of nature implies knowing them. During the Renaissance and long after, the ideas of omniscience and omnipotence were closely linked, as they still are in the minds of a great many scientists and non-scientists. Only very recently, with the new sciences of instability and chaos, has this connection been called into question. The emotional element was quite evident during that formative period of Western science, but since the end of the eighteenth century, the emphasis has been on reason, on logical necessity. Kant doubted that there was any such thing as scientific creativity. The laws of nature had been deciphered once and for all by Newton; all that remained was to apply them to an ever wider range of phenomena. Today we know that this triumph of classical science was ephemeral—our contemporary view of time, space and matter has little in common with Newton's.

Yet the idea of a "limited" creativity persists. Thomas Kuhn, in his famous book, *The Structure of Scientific Revolutions,* distinguishes between two different states in the activities of scientific communities: *normal* periods and the "anomalous" periods he associated with paradigm changes. New paradigms come forth only when contradictions appear and force scientists to revise their hypotheses, and only then are emotions triggered.

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There are certainly examples that bear out Kuhn's thesis: one is the discovery of Planck's constant at the beginning of this century. But I think that on the whole, scientific creativity is far from being limited to paradigm shifts in Kuhn's sense. No contradictions appeared in physics when Boltzmann inserted the arrow of time into the structure of physics, or when Mach sought to rethink the limits of mechanics by questioning the principle of inertia. And what about Einstein's relativity (to which we shall return)? Was it not an attempt to realize a grandiose dream—that of putting all of physics in geometric terms—that harks back to both the Platonic and Cartesian traditions?

I mentioned the impact of Newton's synthesis: I believe it was in itself a curious amalgam of reason and passion. The most important part of Newton's synthesis was his enunciation of a law of nature. This altogether original concept is peculiar to the Western scientific view. Newton's principle links forces with acceleration. This principle—verified a thousand times over, and the basis for all further extensions (quantum or relativistic mechanics)—has two essential characteristics: it is deterministic, and it is reversible in time. Being deterministic means that if we know a material body's initial conditions, we can calculate its position at any moment in the future or in the past. Being reversible means that future and past play the same role. However, these characteristics—especially time-reversibility—seem to contradict outright everything we see around us. Whether at the level of our own experience, or in the phenomena around us—in chemistry, geology or biology—past and future play different roles. Everywhere we see the arrow of time; how could it have issued from non-time, from a fundamental law that ignores time? This is a subject that has interested me throughout my scientific career. In view of this radical negation of time, it seems to me that the particular position of dynamics cannot be understood without appealing to emotional elements. In a recently published book, Isabelle Stengers and I wrote,

> Perhaps we need to start by emphasizing the almost inconceivable character of dynamic reversibility. The question of time—of what its flow preserves, creates and destroys—has always been at the centre of human concerns. Much speculation has called the idea of novelty into question and affirmed the inexorable linkage between cause and effect. Many forms of mystic teaching have denied the reality of this changing and uncertain world, and defined an ideal existence permitting escape from life's afflictions. And we know how important the idea of cyclic time was in antiquity. But, like the rhythm of the seasons or the generations of man, this eternal return to the point of origin is itself marked by the arrow of time. No speculation, no teaching has ever affirmed an equivalence between what is done and what is undone, between a plant that sprouts, flowers and dies, and a plant that resuscitates, grows younger and returns to its original seed; between a man who grows older and learns, and one who becomes a child, then an embryo, then a cell.

Yet Newtonian dynamics—the theory that became identified with the triumph of science—implied this radical negation of time right from the outset. I think we can find the roots of this negation in the theological conceptions of Newton's day. Leibniz, for one, held that God knows no distinction among past, present and future. "A sufficiently informed person," he wrote, echoing Saint Thomas, "could at any given time predict the whole future." (It is worth noting that Leibniz lived a hundred years before Laplace.) Since for God there is no such thing as time, there should not be for the well-informed scientist either. Thus the negation of time became part of the scientist's credo. Even today, most scientists share this opinion; at any rate, it is the point of view expressed in the works of Feynman, Hawking and David Ruelle: fundamental laws ignore the arrow of time. Phenomenology rejects the arrow of time in the same way. But what is a science that casts life, and we who create this science, into phenomenology?

How can we accept, as Einstein did, both the idea that determinism reigns absolute and the idea that the creation of theory is due to the free play of the human mind? I think this is an example of an emotional attitude that clearly marks the limits of reason. I have always been fascinated by this paradox of time, and I would like to say something about it now.

Let us go back to the nineteenth century, in particular the years following Darwin's publication of *The Origin of Species* (1859). This work introduced into the sciences a new paradigm based on the idea of evolution. Darwin not only sought to demonstrate the fact of evolution, but also suggested what the underlying mechanism, based on fluctuations and amplification, might be.

Six years later, Clausius's enunciation of the Second Law of Thermodynamics came about, in a way, as physics' answer to biology. The Second Law classifies physical phenomena as either reversible or irreversible in time; the latter produces entropy. Hence Clausius's celebrated principle: entropy in the Universe is increasing. (In the thought of that day, the Universe was the isolated system par excellence.)

Few physicists or mathematicians took Clausius's law seriously. Boltzmann was an exception. For him, the nineteenth century was the century of Darwin, and the notion of evolution was an essential element in the description of nature. He tried to go further and give a dynamic interpretation of the increase of entropy. I shall not go into the details, because the examples Boltzmann studied, from the kinetic theory of gases, are in all the textbooks.

Like Darwin, Boltzmann thought that irreversibility occurs at the level of populations. Collisions between molecules lead a large system, such as a gas, to a state of equilibrium. But the publication of Boltzmann's findings triggered a crisis. Did it not run counter to logic to try to infer the irreversibility of dynamic laws which, as Newton had shown, are reversible in time? The great mathematician Henri Poincaré had very harsh words to say about this: he thought Boltzmann's effort was self-contradictory right from the start. This negative judgment should have provoked a crisis in physics, since it called into question the very basis of our thinking. What does it mean to think if there is no flow of time? And do we not know today that the brain is actually a time-oriented organ? The future, our plans for tomorrow, are processed in a different part of the brain than the one that stores our memories. Oddly enough, Boltzmann's defeat was considered a triumph. A triumph of nontemporal vision. Did Einstein not repeatedly say, "Time [as irreversibility] is an illusion"?

This brings us to the personality of Einstein, who I believe illustrates better than anyone else the conflict between reason and passion. Why did he try at all costs to eliminate time as irreversibility from the fundamental equations of physics? He knew well enough that, like everyone else, he was getting older day by day. What did it mean for him to say that time is an illusion? Perhaps he was expressing his faith in our symbols: if there was no time direction in the relativity equations he wrote, that was because there was no time in the Universe. But this does not explain why it was so important to eliminate time. A passage in which Einstein explains what scientists are may help us understand his motive. Describing the people who the Angel of God would spare if ordered to drive the unworthy from the Temple of Science, he says,

> Most of them are odd, introverted and lonely individuals who, despite their common traits, actually resemble each other less than do those who have been driven out. What led them to the Temple? . . . One of the most powerful motives that drive people to art and science is the urge to get away from a humdrum existence, with its pain and desperate void, to escape from the bonds of ceaselessly changing personal desires. It drives sensitive people to transcend their personal existence and seek the world of contemplation and objective knowledge. This motive is comparable to the ardent desire that draws a city-dweller out of his noisy, chaotic surroundings to the peace that reigns on the mountain heights, where his eye roams far through the calm, pure air and caresses the peaceful lines that seem created for eternity. But besides this negative motive, there is another, positive one. Man tries to shape for himself, in some adequate way, a simple and clear image of the world, and to triumph over the world of experience by replacing it, to some extent, with this image.

Thus science appears to be a way to escape from reality, to withdraw from a world fraught with self-interest and conflict. Boris Kusnetsov has written an interesting account of Dostoyevski's influence on Einstein, who said repeatedly that he owed more to Dostoyevski than to any other thinker. This may seem odd, but it becomes clearer if we think of Einstein's basically pessimistic attitude towards the problems of existence. He was a very lonely man who acknowledged few friends and a few students, and had, he said, difficult relationships with both his wives. We might add that he saw the onslaught of anti-Semitism and the nightmares of two World Wars. It is hardly surprising, then, that he thought of Dostoyevski as a witness of human suffering, especially the absurd facet manifested in cruelty to animals and children. Einstein clearly expressed his deep-rooted attitude that for him, as it had been ages before for Lucretius and Epicurus, science was a way of escaping from the human condition and contemplating the splendors of reason at work in nature. In 1916, when Einstein was seriously ill, he told Max Born's wife, who had asked him about the fear of death, that he felt such solidarity with every living thing that it mattered nothing to him to know when a particular existence within this infinite becoming began or ended.

According to Kusnetsov, it was by extending Dostoyevski's pessimism that Einstein came to place the universality of law above the existence of individual beings. We must bow before the beauty of this vision, but today we can better measure its fragility.

We are all familiar with Einstein's scientific itinerary: first special relativity, then generalized relativity, leading to an extraordinary synthesis linking matter, space and time. And lastly, the application of these ideas to cosmology. In accordance with his belief, Einstein suggested the existence of a static universe, in some way the realization of Spinoza's ideas at the level of the Universe. Einstein thus aspired to describe the Universe in geometric terms. He took up, in a new way, Descartes's idea of the world as extension, in contrast to the world of thought. History teaches, however, that all dualism is fragile, and Einstein's geometric universe was to turn unexpectedly into a temporal universe, an evolving universe of which the famous residual radiation at three absolute degrees is probably the most direct proof.

Doubtless Einstein best embodies the ideal that defines this vocation of physics—the ideal of a knowledge that strips from our conception of the world everything that he saw as merely the sign of human subjectivity. The ambition of certain mystical practices has always been to escape from life's bonds, from the torments and disappointments of a changing and deceptive world. In a way, Einstein took this ambition to be the physicist's vocation and, in so doing, translated it into scientific terms. Mystics seek to experience the world as an illusion; Einstein intended to demonstrate that it is indeed no more than an illusion, and that truth is a transparent and intelligible universe purified of all that affects human life: nostalgia or painful memory of the past, dread or hope of the future.

But this idea of liberating man from dread or hope of the future stems from a profoundly pessimistic position. What is man's role? To withdraw from this world, or to participate in the construction of a better one? Science—which, as we have seen, began under the sign of a Promethean affirmation of the power of reason—thus ended in alienation. What can man do in a deterministic universe in which he is a stranger? This is the anxiety expressed in so many recent writings, like those of Jacques Monod, who speaks of man as a gypsy on the outskirts of the Universe, or of Richard Tarnas, who writes "For the deepest passion of the Western mind has been to reunite with the ground of its being." I believe this is true, and that our period is indeed one of reunification, of a quest for unity—witness the deep interest in nature shown by so many young people today, and man's growing sense of solidarity with all living beings. To exemplify the transition towards this new stage, I shall tell you something of my own personal experience.

I received a humanistic education, and my adolescence was marked by political insecurity; this made me all the more sensitive to time as the framework for changes in the human condition. I was an avid reader of Bergson, and his famous "Time is invention or it is nothing" remains engraved in my memory. During my scientific studies at the Free University of Brussels, I may have felt, without altogether realizing it, how difficult it is to accept a science in which time is only an illusion. As Karl Popper, another witness of our times, has written, such a conception "brands unidirectional change as an illusion. This makes the catastrophe of Hiroshima an illusion. This makes our world an illusion, and with it all attempts to find out more about our world."

In effect, I felt the same shock that Bergson did, and my intellectual career was similarly placed under the sign of the study of time. But, faced with the same dilemma, I reacted differently. Far from wishing to assign limits to science and restrict it to the study of reversible phenomena, I was convinced that if science studied only these, it was because it was treating only overly simple phenomena in which irreversibility had no part. Hence my conviction that irreversibility would make its entrée into science only with complex phenomena.

My work began with traditional thermodynamics, as expanded by Théophile De Donder, my teacher. I was struck by the constructive role of nonequilibrium situations. We can find a simple example of this in the thermodiffusion effect, which shows how the production of entropy generally has a dual role corresponding to the simultaneous creation of order and disorder. Let us take a system with two components, hydrogen and nitrogen, mixed homogeneously in a container with two compartments, A and B. If we subject this system to a heat flow from outside, the external constraint imposes a temperature gradient inside the system. The thermodiffusion effect consists of the fact that one of the components, say the hydrogen, will concentrate in compartment A, and the other in compartment B. Even in this simple case, we

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have two coupled phenomena at work. The heat flow leads to a positive production of entropy, but the diffusion acts like concentration gradients (this is what is called the thermodiffusion effect); were it able to act alone, not coupled to the other process, it would lead to a negative production of entropy. This effect shows that irreversibility is a dual phenomenon, for it corresponds to dissipation (there the heat flow) and the formation of order (here the thermal diffusion).

This is, of course, only a very simple example, but one that struck me forcefully and, in some ways, oriented my scientific itinerary, leading me first to study the constructive effects of nonequilibrium.

Today nonequilibrium physics is in full development. Surprise follows surprise: regular temporal structures, oscillating chemical reactions, irregular temporal structures (dissipative Chaos), spatial (or Turing) structures. The constructive role of nonequilibrium is now an established fact, but how can it be reconciled with the essential contents of Newton's Law, which implies equivalence between past and future? As I said before, this is the paradox of time. The time paradox is closely related to others—the quantum paradox, the cosmological paradox—which in the last analysis are also linked to the role of time. In a nutshell, the quantum paradox derives from the fact that the fundamental equation in quantum mechanics is symmetrical in time, hence it is our measurements, our interventions that give direction to time. In quantum mechanics, man is the father, rather than the child, of time. Modern cosmology also posed the problem of time, but in a highly dramatic way, with the discovery of the big bang. What could be more irreversible than the transition from a pre-universe to a universe such as the one we know? This is not the place to go further into these problems; they are studied in detail in my book *Time, Chaos and the Quantum.*

Clearly, we must face up to the fact that the very notion of a law of nature must be revised. We can no longer be content with laws that affirm an equilibrium between past and future. In this paper I have dealt mainly with the ideological conflict between reversible time (as formulated, for instance, in Newtonian physics) and irreversible becoming (as it appears in thermodynamics). How can we go beyond the superb intellectual monuments represented by classical, quantum and relativistic physics? This is where a major event—the renovation of classical dynamics following Poincaré's fundamental works in the nineteenth century and those of Kolomogorov and many others in the twentieth—played a great role. Their studies made it plain that not all dynamic systems are similar. Dynamic systems cannot be limited to regular or periodic examples such as the pendulum or the movements of the planets.

To the contrary, most dynamic systems are unstable. The trajectories fly apart exponentially, so far that their traces are inevitably lost after a certain amount of time. These discoveries refute the objections once made to Boltzmann's work. And as my colleagues and I have tried to show, one can go further and formulate laws of dynamics that account for this chaos. However, these laws apply only to wholes, to statistical situations, not to trajectories (or individual wave functions).

Laws so conceived tell us not what is going to happen, but what may happen. Consider the Universe at its inception. Was it not like a small child who might become a musician, a lawyer or a shoemaker, but not all of these things at once? So irreversibility seems to be based on instability. This, of course, leads to a substantial unification of our image of the world, making all of nature's varied aspects consistent with each other.

Here in this room we have air—a gaseous mixture in equilibrium—and we have living beings: nonequilibrium systems par excellence. This variety is made possible only by the constructive role of the arrow of time, which shows the fundamental distinction between the properties of matter in equilibrium and in nonequilibrium.

Such a formulation, which takes account of instability and fluctuations, also transcends the traditional conflict between the "two cultures," for the so-called human sciences cannot be organized without the fundamental notion of evolution.

CONCLUSION

It is time to end.

Science is a dialogue between man and nature. A dialogue, not a soliloquy, as the conceptual transformations to which we have been led over the past few decades have shown. Indeed, science is part of that search for the transcendental that is common to so many cultural activities: art, music, literature.

This relationship to the transcendental has haunted man since paleolithic times. The questions were not posed in vain; they have led to what we consider the most striking manifestations of human creativity in all domains. Each domain has it own specific aspects, of course, just as each historical period has its own outlook. Sometimes we live mainly on the heritage of the past, and explore its wealth; this is when science is "reason." At other times we seek new perspectives, and try to guess what direction we are going to take. These are the times when passion and reason mingle inextricably.

Let us go back to Jacques Monod. At the end of *La nouvelle alliance,* Isabelle Stengers and I wrote,

> Jacques Monod was right: the ancient animistic alliance is indeed dead, and with it all the others that saw us as voluntary, conscious subjects, each with our own projects, each enclosed in a stable identity and longstanding customs, all citizens of a world made for us. That purposeful, static and harmonious world was destroyed by the Copernican revolution when it hurled the earth into infinite space. Nor is our world that of the "modern alliance": the silent, monotonous world from which ancient spells had been cast out, the clockwork world over which we had supposedly been given jurisdiction. Nature was not made for us, or delivered up to our whim. As Jacques Monod says, the time has come for us to assume the risks of human adventure, but if we are able to do so, that is because this is the way in which we now participate in cultural and natural evolution. This is the lesson nature teaches, would we but listen. Scientific knowledge, drawn from the dreams of inspired—that is supernatural—revelation, can be seen today as at once the "poetic echo" of nature and a natural process within nature: an open process of production and invention in an open, productive and inventive world. The time has come for new alliances—ties that have always existed but were long misunderstood—between the history of man, human societies, human knowledge, and the adventure of exploring nature.

Our time is one of expectation, of anxiety, of bifurcation. Far from an "end" of science, I feel our period will see the birth of a new vision, of a new science whose cornerstone encloses the arrow of time; a science that makes of us and our creativity the expression of a fundamental trend in the universe.

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