Ilya Prigogine, *The End of Certainty – Time, Chaos, and the New Laws of Nature*
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Introduction

A New Rationality?

Earlier in this century in *The Open Universe: An Argument for Indeterminism*, Karl Popper wrote, "Common sense inclines, on the one hand, to assert that *every* event is caused by some preceding events, so that every event can be explained or predicted. . . On the other hand, . . . common sense attributes to mature and sane human persons. . . the ability to choose freely between alternative possibilities of acting."[1] This "dilemma of determinism," as William James called it, is closely related to the meaning of time.[2] Is the future given, or is it under perpetual construction? A profound dilemma for all of mankind, as time is the fundamental dimension of our existence. It was the incorporation of time into the conceptual scheme of Galilean physics that marked the origins of modern science.

This triumph of human thought is also at the root of the main problem addressed by this book: the denial of what has been called the *arrow of time.* As is well known, Albert Einstein often asserted, "Time is an illusion." Indeed time, as described by the basic laws of physics, from classical Newtonian dynamics to relativity and quantum physics, does not include any distinction between past and future. Even today, for many physicists it is a matter of faith that as far as the fundamental description of nature is concerned, there is no arrow of time.

Yet everywhere—in chemistry geology, cosmology biology and the human sciences—past and future play different roles. How can the arrow of time emerge from what physics describes as a time-symmetrical world? This is the *time paradox*, one of the central concerns of this book.

The time paradox was identified only in the second half of the nineteenth century after the Viennese physicist Ludwig Boltzmann tried to emulate what Charles Darwin had done in biology in an effort to formulate an evolutionary approach to physics. The laws of Newtonian physics had long since been accepted as expressing the ideal of objective knowledge. As they implied the equivalence between past and future, any attempt to confer a fundamental meaning on the arrow of time was resisted as a threat to this ideal. Isaac Newton's laws were considered final in their domain of application, somewhat the way quantum mechanics is now considered to be final by many physicists. How then can we introduce unidirectional time without destroying these amazing achievements of the human mind?

Since Boltzmann, the arrow of time has been relegated to the realm of phenomenology. We, as imperfect human observers, are responsible for the difference between past and future through the approximations we introduce in our description of nature. This is still the prevailing scientific wisdom. Certain experts lament that we stand before an unsolvable mystery for which science can provide no answer. We believe that this is no longer the case because of two recent developments: the spectacular growth of nonequilibrium physics and the dynamics of unstable systems, beginning with the idea of chaos.

Over the past several decades, a new science has been born, the *physics of nonequilibrium processes,* and has led to concepts such as *self-organization* and *dissipative structure,* which are widely used today in a large spectrum of disciplines, including cosmology, chemistry, and biology, a well as ecology and the social sciences. The physics of nonequilibrium processes describes the effects of unidirectional time and gives fresh meaning to the term irreversibility. In the past, the arrow of time appeared in physics only through simple processes such as diffusion or viscosity, which could be understood without any extension of the usual time—reversible dynamics. This is no longer the case. We now know that irreversibility leads to a host of novel phenomena, such as vortex formation, chemical oscillations, and laser light, all illustrating the essential *constructive* role of the arrow of time. Irreversibility can no longer be identified with a mere appearance that would disappear if we had perfect knowledge. Instead, it leads to coherence, to effects that encompass billions and billions of particles. Figuratively speaking, matter at equilibrium, with no arrow of time, is "blind," but with the arrow of time, it begins to "see." Without this new coherence due to irreversible, nonequilibrium processes, life on earth would be impossible to envision. The claim that the arrow of time is "only phenomenological," or subjective, is therefore absurd. We are actually the children of the arrow of time, of evolution, not its progenitors.

The second crucial development in revising the concept of time was the formulation of the physics of unstable systems. Classical science emphasized order and stability; now, in contrast, we see fluctuations, instabi1ity, multiple choices, and limited predictability at all levels of observation. Ideas such as chaos have become quite popular, influencing our thinking in practically all fields of science, from cosmology to economics. As we shall demonstrate, we can now extend classical and quantum physics to include instability and chaos. We are then able to obtain a formulation of the laws of nature appropriate for the description of our evolving universe, a description that contains the arrow of time, since past and future no longer play symmetrical roles. In the classical view—and here we include quantum mechanics and relativity—laws of nature express certitudes. When appropriate initial conditions are given, we can predict with certainty the future, or "retrodict" the past. Once instability is included, this is no longer the case, and the meaning of the laws of nature changes radically, for they now express possibilities or probabilities. Here we go against one of the basic traditions of Western thought, the belief in certainty. As stated by Gerd Gigerenzer et al. in *The Empire of Chance,* "Despite the upheavals in science in the over two millennia separating Aristotle from the Paris of Claude Bernard, they shared at least one attitude of faith: Science was about causes, not chance. Kant even promoted universal causal determinism to the status of a necessary condition of all scientific knowledge."[3]

There were, however, dissenting voices. The great physicist James Clerk Maxwell spoke of a "new kind of knowledge" that would overcome the prejudice of determinisrn.[4] But, on the whole, the prevailing opinion was that probabilities were states of mind rather than states of the world. This is so even today in spite of the fact that quantum mechanics has included statistical concepts in the core of physics. But the fundamental object of quantum mechanics, the *wave function,* satisfies a deterministic, time-reversible equation. To introduce probability and irreversibility, the orthodox formulation of quantum mechanics requires an observer.

Through his measurements, the observer would bring irreversibility to a time—symmetric universe. Again, as in the time paradox, we would be responsible in some sense for the evolutionary patterns of the universe. This role of the observer, which gave quantum mechanics its subjective flavor, was the main reason that prevented Einstein from endorsing quantum mechanics, and it has since led to unending controversies.

The role of the observer was a necessary concept in the introduction of irreversibility, or the flow of time, into quantum theory. But once it is shown that instability breaks time symmetry, the observer is no longer essential. In solving the time paradox, we also solve the quantum paradox, and obtain a new, realistic formulation of quantum theory. This does not mean a return to classical deterministic orthodoxy; on the contrary, we go beyond the certitudes associated with the traditional laws of quantum theory and emphasize the fundamenta1 role of probabilities. In both classical and quantum physics, the basic laws now express possibilities. We need not only *laws,* but also *events* that bring an element of radical novelty to the description of nature. This novelty leads us to the "new kind of knowledge" anticipated by Maxwell. For Abraham De Moivre, one of the founders of the classical theory of probabilities, chance can neither be defined nor understood.[5] As we shall illustrate, we are now able to include probabilities in the formulation of the basic laws of physics. Once this is done, Newtonian determinism fails; the future is no longer determined by the present, and the symmetry between past and future is broken. This confronts us with the most difficult questions of all: What are the roots of time? Did time start with the "big bang"? Or does time preexist our universe?

These questions place us at the very frontiers of space and time. A detailed explanation of the cosmological implications of our position would require a special monograph. Briefly stated, however, we believe that the big bang was an event associated with an instability within the medium that produced our universe. It marked the start of our universe but not the start of time. Although our universe has an age, the medium that produced our universe has none. Time has no beginning, and probably no end.

But here we enter the world of speculation. The main purpose of this book is to present the formulation of the laws of nature within the range of low energies. This is the domain of macroscopic physics, chemistry, and biology. It is the domain in which human existence actually takes place.

The problems of time and determinism have remained at the core of Western thought since the pre-Socratics. How can we conceive of human creativity or ethics in a deterministic world?

This question reflects a profound contradiction in Western humanistic tradition, which emphasizes the importance of knowledge and objectivity, as well as individual responsibility and freedom of choice as implied by the ideal of democracy. Popper and many other philosophers have pointed out that we are faced with an unsolvable problem as long as nature is described solely by a deterministic science.[6] Considering ourselves as distinct from the natural world would imply a dualism that is difficult for the modern mind to accept. Our aim in this work is to show that we can now overcome this obstacle. If "the passion of the western world is to reunite with the ground of its being' as Richard Tarnas has written, perhaps it is not too bold to say that we are closing in on the object of our passion.[7]

Mankind is at a turning point, the beginning of a new rationality in which science is no longer identified with certitude and probability with ignorance. We agree completely with Yvor Leclerc when he writes, "In the present century we are suffering from the separation of science and philosophy which followed upon the triumph of Newtonian physics in the eighteenth century.[8] Jacob Bronowski beautifully expressed the same thought in this way: "The understanding of human nature and of the human condition within nature is one of the central themes of science."[9]

At the end of this century, it is often asked what the future of science may be. For some, such as Stephen W. Hawking in his *Brief History of Time,* we are close to the end, the moment when we shall be able to read the "mind of God."[10] In contrast, we believe that we are actually at the beginning of a new scientific era. We are observing the birth of a science that is no longer limited to idealized and simplified situations but reflects the complexity of the real world, a science that views us and our creativity as part of a fundamental trend present at all levels of nature.

References

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