D. Layzer : Cosmogenesis.

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The Unity of Science

The Problem of Order

Around the beginning of the sixth century B.C., in the prosperous trading center of Miletus on the Aegean coast of present-day Turkey, a handful of Greek thinkers made the first recorded efforts to construct a rational or nonmythical account of how order arose in the world. It seemed obvious to them that the world could not have sprung from emptiness. "Nothing," they were fond of saying, "comes from nothing." It seemed equally obvious that the world didn't spring into being ready-made: the *kosmos,* they all agreed, must have evolved from a primordial chaos. (In classical Greek, *kosmos* means both "order" and "world.") But how? Western science and Western philosophy have their roots in the efforts of Thales, Anaximander, Anaximenes, and their successors to answer this question.

Philosophers have long since ceded the question to natural scientists, who, following science's oldest and most fruitful methodological precept, divide and conquer, have separated it into more specific questions:

- How can we account for the permanence, stability, and orderliness of crystals, molecules, atoms, and subatomic particles?
- How did the complex hierarchic structure of the astronomical Universe come into being?
- What is the origin of biological organization in all its manifestations, from DNA to the human mind?
- And why do most kinds of order tend to crumble and decay?

These four questions are central to four great divisions of natural science: quantum physics, cosmology, biology, and macroscopic physics or thermodynamics. These

disciplines have yielded a deeper and more detailed understanding of order in its varied manifestations than anyone could have anticipated, even fifty years ago. There are gaps, of course. Theoretical physicists are still striving to unify the laws of physics; the origin of life is still a mystery; and the origin of astronomical systems remains an area of speculation and controversy. These problems lie at the frontiers of modern science, and they are getting a lot of attention.

But another kind of incompleteness in natural science's picture of the world has received less attention: *the four great pieces of the picture don't quite fit together.* Each piece, although still incomplete, is remarkably coherent. Each piece is connected to other pieces. But the connections aren't smooth. There are deep unresolved conflicts between quantum physics and macroscopic physics, between macroscopic physics and cosmology, and between the physical sciences and biology.

Conflicts and Paradoxes

The relation between quantum physics, which describes the invisible world of elementary particles and their interactions, and macroscopic physics, which describes the world of ordinary experience, has perplexed physicists since the birth of quantum physics in 1925. Viewed as a system of mathematical laws, quantum physics includes macroscopic physics as a limiting case. By that I mean that quantum physics and macroscopic physics make the same predictions in the domain where macroscopic physics has been strongly corroborated (the macroscopic domain), but quantum physics also successfully describes the behavior and structure of molecules, atoms, and subatomic particles (the microscopic domain). Yet from another point of view, macroscopic physics seems more fundamental than quantum physics. As we will see later, the laws of quantum physics refer explicitly to the results of measurement. But every measurement necessarily has at least one foot in the world of ordinary experience: it has to be recorded in somebody's lab notebook or on magnetic tape. So quantum physics seems to presuppose its own limiting case—macroscopic physics. This is the mildest of several paradoxes that have sprung up in the region where quantum physics and macrophysics meet and overlap.

The relation between macrophysics and cosmology is also problematic. The central law of macroscopic physics—the second law of thermodynamics—was understood by its inventors, and is still understood by most scientists, to imply that the Universe is running down—that order is degenerating into chaos. How can we reconcile such a tendency with the fact that the world is full of order—that it is a *kosmos* in both senses of the word? Some scientists say, "The contradiction is only apparent. The Second Law assures us that the Universe is running down, so it must have begun with a vast supply of order that is gradually being dissipated." But this way of trying to resolve the difficulty takes us from the frying pan into the fire, because, as we will see, modern cosmology strongly suggests that the early Universe contained far less order than the present-day Universe.

Astronomical evolution and biological evolution are both stories of emerging order. Nevertheless, the views of time and change implicit in modern physics and modern biology are radically different. The physical sciences teach us that all natural phenomena are governed by mathematical laws that connect every physical event with earlier and later events. Imagine that every past and future event was recorded on an immense roll of film. If we knew all the physical laws, we could reconstruct the whole film from a single frame. And in principle there is nothing to prevent us from acquiring complete knowledge of a single frame.

This worldview is epitomized in a much-quoted passage by one of Newton's most illustrious successors, the mathematician and theoretical astronomer Pierre Simon de Laplace (1749–1827):

> We ought then to regard the present state of the Universe as the effect of its previous state and the cause of the one that follows. An intelligence that at a given instant was acquainted with all the forces by which nature is animated and with the state of the bodies of which it is composed would—if it were vast enough to submit these data to analysis—embrace in the same formula the movements of the largest bodies in the Universe and those of the lightest atoms: Nothing would be uncertain for such an intelligence, and the future like the past would be present to its eyes. The human mind offers, in the perfection it has been able to give to astronomy, a feeble idea of this intelligence.[1]

Much the same view of the world was held by Albert Einstein:

> The scientist is possessed by the sense of universal causation. The future, to him, is every whit as necessary and determined as the past.[2]

Most contemporary physical scientists would probably agree with Laplace and Einstein. The world they study is a *block universe*, a four-dimensional net of causally connected events with time as the fourth dimension.[3] In this world, no moment in time is singled out as "now." For Laplace's Intelligence, the future and the past don't exist in an absolute sense, as they do for us.

How does life, regarded as a scientific phenomenon, fit into this worldview? A modern Laplacian might reply:

> Living organisms are collections of molecules that move and interact with one another and with their environment according to the same laws that govern molecules in nonliving matter. A supercomputer, supplied with a complete microscopic description of the biosphere and its environment, would be able to predict the future of life on Earth and to deduce its initial state. Implicit in the present state of the biosphere and its environment are the precise conditions that prevailed in the lifeless broth of organic molecules in which the first self-replicating molecules formed. And implicit in the conditions that prevailed in that broth and its environment is every detail of the living world of today.

If you believe that living matter is subject to the same laws as nonliving matter—and few, if any, contemporary biologists would dispute this assertion—this argu-

ment may seem compelling. Yet it clashes with two key aspects of the evolutionary process as described by contemporary evolutionary biologists: randomness and creativity.

Randomness is an essential feature of the reproductive process. In nearly every biological population, new genes and new combinations of genes appear in every generation. Reproduction, whether sexual or asexual, involves the copying of genetic material (DNA). In all modern organisms the copying process is astonishingly accurate. But it isn't perfect. Occasionally there are copying errors, and these have a random character. In sexually reproducing populations there is another source of randomness: the genetic material of each individual is a random combination of contributions from each parent.

The *creative* factor in biological evolution is natural selection, the tendency of genetic changes that favor survival and reproduction to spread in a population, and of changes that hinder survival and reproduction to die out. From the raw material provided by genetic variation, natural selection fashions new biological structures, functions, and behaviors.

A mainstream physicist might reply that the apparent randomness of genetic variation is just a consequence of human ignorance—our inability to understand exceedingly complex but nevertheless completely determinate causal processes—and that evolution is "creative" only in a metaphorical sense. According to this view, evolution merely brings to light varieties of order prefigured in the prebiotic broth.

There is an even more fundamental difference between the physical and the biological views of reality: the physicist's picture of reality seems impossible to reconcile with subjective experience. For there is nothing in the neo-Laplacian picture that corresponds to the central feature of human experience, the passage of time. We humans must watch the film unwind, but Laplace's Intelligence sees it whole. Nor is there anything that corresponds to the aspect of reality (as we experience it) that Greek philosophers called *becoming*, as opposed to the timeless *being* of numbers, triangles, and circles. The universe of modern physics is an enormously expanded and elaborated version of the perfectly ordered but static and lifeless world we encounter in Euclid's *Elements*, of which it is indeed a direct descendant. The biologist's world seems entirely different. Life, as we experience it, is inseparable from unpredictability and novelty.

Freedom and Necessity

What is the relation between being and becoming? Is the future as fixed and immutable as the past? What is chance? These questions bear on one of the perennial problems of Western philosophy, the problem of freedom and necessity.

Each of us belongs to two distinct worlds. As objects in the world that natural science describes we are governed by universal laws. To Laplace's Intelligence we are systems of molecules whose movements are no less predictable and no more the results of free choice than the movements of the planets around the Sun. But as the subjects of our own experience we see the world differently: not as bundles of events frozen into the block universe of Laplace and Einstein like flies in amber, but as the authors of our own actions, the molders of our own lives. However strongly we may believe in the universality of physical laws, we cannot suppress the intuitive conviction that the future is to some degree open and that we help to shape it by our own free choices.

This conviction lies at the basis of every ethical system. Without freedom there can be no responsibility. If we are not really free agents—if our felt freedom is illusory—how can we be guided in our behavior by ethical precepts? And why should society punish some acts and reward others? The Laplacian worldview tends to undermine the basis for ethical behavior.

Judeo-Christian theology faces a similar problem. Although Laplace's Intelligence is not the Judeo-Christian God—Laplace's Intelligence observes and calculates; the Judeo-Christian God wills and acts ("Necessitie and chance approach not mee, and what I will is Fate," says the Almighty in Milton's *Paradise Lost*)—they contemplate similar universes. Nothing is uncertain for an all-knowing God, and the future, like the past, is present to His eyes. But if we cannot choose where we walk, why should those who take the narrow way of righteousness be rewarded in the next life while those who take the primrose path are consigned to the flames of hell?

Theologians have not, of course, neglected this question. Augustine, for example, argued that God's foreknowledge (or more accurately, God's knowledge of what *we* call the future) doesn't *cause* events to happen and is therefore consistent with human free will. Other theologians have embraced the doctrine of predestination and argued that free will is indeed an illusion. Still others have taken the position that divine omniscience and human free will are compatible in a way that surpasses human understanding.

Reconciling the scientific and ethical pictures of the world was a concern of the first scientists. Our scientific picture of the world was foreshadowed by Greek atomism, a theory invented by the natural philosophers Leucippus and Democritus in the fifth century B.C. According to this theory, the world is made up of unchanging, indestructible particles moving about in empty space and interacting with one another in a completely deterministic way. Like modern biologists, Democritus believed that we, too, are assemblies of atoms. Yet Democritus also elaborated a system of ethics based on moral responsibility. He taught that we should do what is right not from fear, whether of punishment or of public disapproval or of the wrath of gods, but in response to our own sense of right and wrong. Unfortunately, the surviving fragments of Democritus's writings don't tell us how or whether he was able to reconcile his deterministic picture of nature with his doctrine of moral responsibility.

A century later, another Greek philosopher with similar ideas about physical reality and moral responsibility faced the same dilemma. Epicurus (341–270 B.C.) sought to reconcile human freedom with the atomic theory by postulating a random element in atomic interactions. Atoms, he said, occasionally "swerve" unpredictably from their paths. In modern times, Arthur Stanley Eddington and other scientists have put forward more sophisticated versions of the same idea. According to quantum physics, it is impossible to predict the exact moment when certain

atomic events, such as the decay of a radioactive nucleus, will take place. Eddington believed that this kind of microscopic indeterminism might provide a scientific basis for human freedom:

> It is a consequence of the advent of quantum theory that *physics is no longer pledged to a scheme of deterministic laws*. . . . The future is a combination of the causal influences of the past together with unpredictable elements. . . . [S]cience thereby withdraws its moral opposition to free will.[4]

But neither Epicurus nor Eddington explained what the "freedom" enjoyed by a swerving atom or a radioactive atomic nucleus has to do with the freedom of a human being to choose between two courses of action. Nor has anyone else.

The apparent incompatibility between human autonomy and natural necessity can be used to support either of two opposite conclusions: because we are part of nature, autonomy must be an illusion; or because autonomy is a fact, we can't belong entirely to nature—human nature must have a spiritual or nonmaterial side. The second view was central to the philosophy of Socrates, who taught that mechanistic explanations like those advanced by the atomists don't apply to soul or mind. Socrates's doctrine was taken up and developed by Plato and Aristotle, and it has been dominant in Western philosophy ever since. Immanuel Kant, for example, argued that human autonomy is impossible to understand scientifically, but at the same time impossible to deny. It is the central fact of our existence and an indispensable premise of ethical theory. Whatever the scientific status of human autonomy, said Kant, we cannot help acting "under the idea of freedom,"

The view that human beings have a nonnatural or spiritual dimension is, of course, especially congenial to Judeo-Christian religious thought. But it is precisely this view that Charles Darwin's *The Origin of Species*, published in 1859, called into question. Darwin argued that all living organisms have sprung from one or a very few primitive ancestral populations. He also speculated that the first living organisms arose by entirely natural processes from nonliving matter. Modern biology has enormously strengthened these hypotheses, and today they are accepted by virtually every working biologist. But if humankind belongs wholly to the natural world, then human autonomy—no less a fact today than it was in Kant's day or in Socrates's—must be accounted a natural phenomenon. Thus the problem of reconciling human autonomy and natural necessity presents a challenge to natural science as well as to philosophy.

Science and Philosophy

Although the issues I have been discussing are broadly philosophical, I will approach them more in the spirit of science than in the spirit of philosophy. By training and temperament I am a scientist, not a philosopher. More important, I believe that the questions raised by the disunity of the natural sciences and by the conflict between human autonomy and natural necessity are, at their deepest levels, scientific questions. Let me try to make clear what I consider to be the main

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differences between these two closely related and historically intertwined modes of understanding and explanation.

We may take as exemplars of the two modes two classic Greek texts, Plato's *Republic* and Archimedes's *On the Equilibrium of Floating Bodies.* These books differ in two related ways.

1. Virtually no modern student of physics reads *On the Equilibrium of Floating Bodies;* no serious student of philosophy can afford not to read the *Republic.*

2. Archimedes's treatise unequivocally and correctly answers the question it addresses: What conditions determine the equilibrium configuration of a floating body? Plato's dialogue offers unique and valuable insights into a question that has no correct or final answer: What is justice?

The fact that philosophers rarely succeed in answering the questions they ask doesn't reflect unfavorably on philosophers or philosophy. Philosophy seeks to bring clarity, logical consistency, and order into our thinking about questions that by their very nature can never be finally answered, in part because they take on new meanings as the conditions of our lives and the state of our knowledge change. Natural science is different in this respect. A modern Plato wouldn't reinvent the arguments and conclusions of the *Republic*, but a modern Archimedes, faced with the same questions as the historical Archimedes, would in nearly every case invent the same answers, because they are the *right* answers.

The last assertion may shock some readers. Science, we are often told, doesn't supply *right* answers. Theory B may answer a particular kind of question better than theory A, but theories are ephemeral, and tomorrow theory B may be superseded by theory C. And indeed, Archimedes's theory of static equilibrium has been superseded by Newtonian dynamics, which in turn has been superseded by Einstein's general theory of relativity.

Yet if you want to predict how far a ship can roll without capsizing, you may rely on Archimedes's theory of floating bodies. If you want to predict whether a framework of steel girders will be stable, you may rely on Archimedes's theory of statics. Newton's theory makes the same predictions. So does Einstein's, and—we may be confident—so will the theory that supersedes Einstein's.

How can this be? How can theories as different as Archimedean statics, Newtonian dynamics, and Einstein's general theory of relativity give the same, correct answers to questions that lie in their common domain? And what can we infer about scientific theories and their evolution from the fact that they do agree?

The philosopher Willard Van Orman Quine argues that theories are *underdetermined* by the requirement that their predictions agree with experience—that is, that many different theories are compatible with this requirement.

> We have no reason to suppose that man's surface irritations [sensory information about the external world] even unto eternity admit of any one systematization that is scientifically better or simpler than all possible others. It seems likelier, if only on account of symmetries or dualities, that countless alternative theories would be tied for first place. Scientific method is the way to to truth, but it affords even in principle no unique definition of truth.[5]

Thus, according to Quine, scientific truth has many forms. The historian of science Thomas Kuhn goes further. He concedes that new theories work better than the theories they succeed, but denies that science progresses toward objective truths about the world. In some respects, says Kuhn, Einstein is closer to Aristotle than to Newton.[6]