SUDDEN CHANGE IN THE WORLD

by David W. Oxtoby

Abstract. The suddenness of phase change is examined as an example of a discontinuity in nature, in which an apparently random microscopic event can trigger a macroscopic change of state such as the crystallization of a liquid. Recent advances in nucleation theory that have helped to quantify but not eliminate this randomness are described, and analogies with the modes of God's action in the world are explored.

Keywords: God's action in the world; metastability; phase transitions; randomness; thermodynamics.

Change in the natural world can occur smoothly or abruptly. The gradual evolution of main-sequence stars from a hydrogen-burning to a helium-burning stage takes many millions of years, but the explosion of a supernova reaches its peak in days. Rocks weather over periods of thousands of years, but the sudden violence of a tornado passes in minutes. The corrosion of a slab of iron occurs far more slowly than the explosion of a canister of nitroglycerine. A complete picture of nature must accommodate the sudden and surprising as well as the gradual and continuous.

In the developing dialogue between science and religion, more emphasis has been placed on continuous change. There are good reasons for this. Individuals trying to create bridges from either side to the other have emphasized the continuity of our ways of experiencing the world rather than the differences between them. A holistic view of knowledge has argued (quite correctly) that there are no sharp boundaries between different disciplines. Although there is a growing tendency to reject a reductionist approach (the idea of a

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hierarchy in which biology is reducible to chemistry, chemistry to physics, and so forth), there is still a useful effort to relate problems in one field of inquiry to concepts and laws of other disciplines. The introduction of special forces unique to one part of nature is frowned upon in modern science. To give just one example: theories of "vitalism," which argued for a sharp difference between living and nonliving matter, have been abandoned because they failed to make useful predictions about the real world.

I will argue in this essay, however, that more attention should be paid to *discontinuities* in the world. Not only are they part of nature (and thus must be incorporated in a comprehensive view of the world), but they also provide useful models for understanding religion. I will begin by talking about discontinuities in physics, chemistry, and biology in general terms, and then focus on one particular problem to which I have devoted most of my research efforts: the dynamics of first-order phase transitions. I will use the development of the theory of nucleation in the twentieth century to illustrate aspects shared by many areas of science: the movement from ignorance to understanding, from irrational randomness to regularity, from arbitrariness to a still mysterious simplicity. I will then close by connecting the chemistry and physics of phase transitions in a metaphorical sense to a Christian perspective on the modes of God's action in the world.

DOES NATURE MAKE JUMPS?

It was a longstanding tenet of classical science, stated explicitly by Leibnitz for physics and Linnaeus for botany, that "Nature does not make jumps." A rationalist point of view insists correctly that effects arise out of causes, not from midair. If science is to be predictive, it must be able to project forward from observed behavior, using accepted laws, toward future expectations. Classical Newtonian mechanics is a prime example of a continuous theory in which positions and velocities of particles change smoothly over all allowed values. Through the end of the nineteenth century, it was a tremendously productive assumption to take physical processes to be "well-behaved" in a mathematical sense; the special singularities allowed for in mathematical theories were often simply ignored in physics.

This has changed in the twentieth century. In atomic physics the examination of matter on a microscopic scale has demonstrated its "graininess," in the same way that a close look at a beach reveals individual particles of sand. Charge and mass come in "packets":

Milliken's oil drops could have one, two, or three units of elementary charge on them but not 1.56, and the element carbon comes in packets weighing 1.99265×10^{-23} grams. The science of quantum mechanics has shown that molecules in stationary states can possess only certain discrete values of the energy. The smooth and steady evolution of life forms predicted by Darwin has given way to a more complex model of punctuated evolution, in which long periods of relatively slow development are interrupted by episodes of extremely rapid change. The new science of chaos theory is built about mathematical objects called strange attractors; under the appropriate conditions, dynamical systems make abrupt and seemingly random jumps from one region of phase space to another.

All of these examples show that it is useful in science to look for the abrupt and discrete, for the singular as well as the continuous. I do not want to exaggerate the importance of singularities, of course. The Schrödinger equation of quantum mechanics is a second-order differential equation with many of the same properties of continuity as Newton's equations of classical mechanics, and wave functions evolve continuously in time and space. Ideas of punctuated evolution in biology do not violate the basic principles of genetics or the causal connections between chemical mutation and animal morphology, in spite of what the creationists might wish to think. Still, I feel that an examination of jumps in nature can provide a useful counterpoise to an emphasis on smoothness and perhaps boring continuity.

This point has also been made by Holmes Rolston, III (1992). In his comments on Ian Barbour's work (Barbour 1990), Rolston criticizes process thought for not "allow[ing] for surprises of the first magnitude" (p. 81). As I have above, he gives examples of discrete and discontinuous phenomena in nature, and he suggests that "we do need some occasions of wonder at superb moments of critical turning" (p. 82). He contrasts the weakness of the word *novelty,* employed in process thought, with the power of the term *miracle* and argues that there are events in the world for which the latter name is more apposite.

Phase transitions are prime examples of abrupt changes in the natural world. If ice is held at $-0.001\,°C$ nothing will happen; if it is held at $+0.001\,°C$ it will melt to liquid water. If gaseous sulfur dioxide is compressed at 30°C, when the pressure reaches 4.52 times atmospheric pressure the volume will abruptly collapse to a value more than 100 times smaller as the gas condenses to a liquid. Changes of state between gas, liquid, and solid occur abruptly at fixed temperatures and pressures. These sharp transitions occur because of the cooperative behavior of many molecules; a cluster of ten molecules will not crystallize sharply at a particular transition, although recent research has shown that already with several hundred molecules, the phase-transition behavior of matter in bulk is nearly achieved.

The Dynamics of Phase Changes

The description just given of phase transitions was a little misleading in the following sense: some transitions do not actually occur when they are "supposed" to. Liquid water should freeze at 0°C (32°F), and if you wait long enough, it will do so. If a sample of that water is pure enough, however, then "long enough" means far longer than the age of the universe. Water will crystallize just below 0°C only if a small piece of ice is provided to get it started, or if it is dirty enough that solid particles in it will speed the formation of ice on their surfaces. Liquid water can thus be routinely cooled to −10°C, and with care below −30°C. It can be superheated above its normal boiling point of 100°C and held for extended periods of time without turning to vapor. This behavior is not restricted to water; other liquids show it as well.

Seen from this point of view, phase changes are rather random, unpredictable events. It is almost impossible to anticipate the point at which a given sample will freeze or boil. Among other things, this unpredictability has a major effect on our ability to forecast the weather. On a particular day, and in a particular place, will there be rain, snow, sleet, or hail? As the Lord asks Job,

> Has the rain a father,
>   or who has begotten the drops of dew?
> From whose womb did the ice come forth,
>   and who has given birth to the hoarfrost of heaven?
> —Job 38:28–29

The implication is that these natural changes in the atmosphere (the condensation of water vapor to form drops of rain or dew, the crystallization of water to form ice and frost) are events without proximate natural explanations; only an ultimate cause (God) can be assigned to them.

From the primitive view, the natural world is a mysterious environment in which change occurs for no particular reason other than "the will of God." Scientists have long rejected the pessimistic argument that observed phenomena cannot be accounted for, however, and have developed models and theories that, to varying degrees, are capable of explaining and predicting what actually happens in the world. Only in the last fifty years has such a science developed to understand the first stages in the formation of a new phase and the rates at which that phase change can occur. I will describe briefly the historical development of this science of nucleation, the study of the first appearance of a new phase, and will argue that it has progressed in ways parallel to other fields of science.

Different samples of water freeze or boil at different temperatures. The first step that a scientist takes in the face of this observation is to try to prepare samples that will behave identically in any laboratory in the world—irreproducible results are the bane of science. After samples of water are carefully cleaned, phase changes do not occur so readily, suggesting that different types and amounts of "dirt" are responsible for the varied and seemingly random behavior of these phase transitions. Even carefully cleaned samples show a range of freezing temperatures, though, so the next step taken is to break up the sample of water into an emulsion of tiny drops suspended in an oil. As the emulsion is cooled, drops freeze at different temperatures, but there is a particular temperature (the nucleation temperature) near which a substantial fraction freeze, and below which no liquid drops survive. The last drops to freeze must be those containing no dirt to initiate crystallization, and the measured nucleation temperature is now completely reproducible. Note how the scientist proceeds. The real problem (crystallization of a sample of water) is too difficult to solve, so the scientist shifts focus to a problem that *can* be solved: the freezing of those artificially created droplets in the emulsion that by accident do not contain any dirt. This approach of creating artificially simple and well-behaved systems in order to do reproducible experiments is the hallmark of science.

I do not mean to suggest that scientists are not interested in the real problems of dirty water and how it crystallizes. Indeed, considerable progress has been made in that direction as well. Cloud physicists have collected water droplets from all over the world and analyzed them; they have dissected snowflakes and hailstones to find out what lies at their centers. The current consensus is that one of the main substances causing water drops to form from water vapor in the atmosphere is ammonium sulfate and that tiny clay particles (real dirt) often occur at the centers of ice particles. One of the main areas of focus now is crystallization in polar stratospheric clouds, where the formation of certain particles plays a significant role in depleting the ozone layer in the atmosphere. In all of this work, scientists make progress by greatly restricting the scope of their studies at each stage to artificial problems that are solvable. This is the process of "normal science" in Thomas Kuhn's sense.

Even the artificially created dirt-free worlds designed by scientists cannot be fully controlled, however. Research on nucleation theory has revealed that there is always a random element present, because a fluctuation is required for a droplet to crystallize. Scientists may eventually be able to predict the *average* time for a collection of drops of pure water to crystallize, but they will never be able to predict when a particular drop will do so. There is an irreducible element of randomness in even the most carefully designed experiment. Such randomness plays a central role in the theology developed by Arthur Peacocke. He argues that the unpredictability of natural phenomena on both microscopic and macroscopic levels is what allows nature to explore such a wide range of possible situations. This unpredictability makes the natural world "a matrix within which openness and flexibility and, in humanity, freedom might naturally emerge" (Peacocke 1990, 156).

The evolution of nucleation science is typical of that of many fields. Rational explanation has removed a major portion of the arbitrary randomness that is present in natural phenomena at first glance. The ability to make quantitative predictions remains confined to artificially simple systems created in the laboratory, but at least a qualitative understanding is gained of what happens in the world around. There remains at the core a fundamental randomness that cannot be removed. Has the element of mystery been removed by the rational approach of science? Not in the least. In this field, as in all fields of science, the mystery has only been shifted to a more profound level. Instead of being mystified by irregular and unpredictable events, scientists now stand in awe of the working out of fundamental laws into phenomena of extraordinary beauty and complexity. The first appearance of a crystal from a liquid is a fine example of the underlying mystery in the natural world.

METASTABILITY

Let us now take a step back from the details of first-order phase transformations to examine some basic aspects of stability in nature and their relation to thermodynamics. Liquid water cooled below 0°C is in a *metastable* state. By this term, scientists mean that the water is stable against small perturbations and, therefore, may remain in that state for a lengthy period of time, but it is unstable to a large enough perturbation. There is a driving force for undercooled water to reach its thermodynamically stable state (ice) but a fluctuation is required for this actually to occur. When such a fluctuation arises (or when an external nucleating agent such as a tiny ice crystal is introduced from the outside) the crystallization of the undercooled water can be extremely rapid. Metastable phases can store large amounts of energy, which is released when the transition occurs. Students in first-year chemistry labs are instructed to use boiling chips when they heat solutions to expel the liquid. If not, they risk superheating the liquid to well above its normal boiling point; when vaporization occurs under these circumstances, it can be quite violent, throwing hot liquid out of the container. The boiling chips act as nucleating agents and prevent excessive superheating. Much of the awesome power released in a thunderstorm comes from the energy stored in metastable states of water vapor and water drops, which is released when raindrops and hailstones form.

Metastability is an inherent property of the entire natural world. It reflects the fact that much of the environment is in a state far from chemical and physical equilibrium. An equilibrium world would be a very quiet one, without winds and weather, with mineral deposits dispersed throughout the earth's surface or (in the case of fossil fuels) combined with oxygen in the atmosphere to form a deadly blanket of carbon dioxide. The complex molecules in plants and animals would be broken up to produce gases and water. The actual world is in a state very far from equilibrium, however. From the point of view of the Second Law of Thermodynamics, the entropy of the earth is considerably lower than the maximum allowable value. The earth is maintained in this state by the flux of energy arriving from the sun, which is the source for order. Plants harness the power of the sun in photosynthesis, and animals employ complex metabolic pathways to convert this stored energy from plants into useful forms. It is the gap between the actual low value of the entropy of the earth and the high maximum possible value that allows for change in the world; this gap creates the potential for the evolution of increasingly complex forms of life and for the appearance of civilization and higher consciousness.

The earth's source of order is the sun, which in turn is in a state far from equilibrium in its *nuclear* composition. A star abundant in hydrogen (as is our sun) is in a state of low entropy relative to one in which most of that hydrogen has been converted to helium or to heavier elements. Ultimately, the source for this low entropy must be traced back through the logic of cosmology toward the formation of the universe. This is a controversial and difficult subject, and there are competing theories regarding the initial state of the universe. One beautiful and compelling argument has been put forward by Roger Penrose. He begins (as I have) by tracing the source for low entropy back from the earth to the sun, and then continues back in time to the formation of the sun by the gravitational collapse of gases in interstellar space (Penrose 1989). Moving *backward* in time, the entropy must steadily *decrease* in order to satisfy the Second Law. In a system dominated by forces of gravity, a state with matter distributed uniformly is one of *low* entropy, whereas one with considerable clustering (as the universe is today) has a higher entropy. (A universe full of black holes is the state of highest entropy.) The spatial uniformity of the observed 2.7 K blackbody background radiation (which is a remnant of the Big Bang at the origin of the universe) provides evidence for the remarkably low initial entropy of the universe.

The conclusion toward which Penrose's reasoning leads is that the initial state of the universe was a very special one indeed: a state of extraordinarily low entropy and high order. Penrose actually makes a rough estimate of the probability that such an initial condition would be selected at random out of all possible initial conditions and arrives at an extremely small number:

$$\text{one part in } 10^{10^{123}}$$

In his words, "this now tells us how precise the Creator's aim must have been" in order to select such a special initial universe out of all the available possibilities (Penrose 1989, 344). It is ultimately the low entropy of this special initial state that has allowed all the unfolding of complexity that has taken place in the evolution of the universe.

GOD'S ACTION IN THE WORLD

Phase transitions can occur only after two requirements are met: metastable states must be created that have the potential for change (a driving force arising from the increase in entropy dictated by the Second Law), and a nucleation catalyst must be present to initiate the change of state. In the absense of such a catalyst, the potential for change in a metastable state can remain unfulfilled for an indefinite period; in its presence, the change can often occur with startling rapidity.

Phase change may be a relatively unexplored area in which to understand the way in which God acts in the world. According to the Big Bang theory, the universe began with tremendous potential, with a vast range of possibilities for future evolution. Because it began with low entropy, life could arise. Thermodynamics is a science in which time does not enter; it talks about processes that can occur, and about driving forces for change, but not about the time scale on which these will take place. It is an appropriate perspective from which to view the cosmic Creator, the God of continuous time (Greek χρονοσ), for whom "a thousand years are . . . like a watch in the night."

The incarnation may be understood through the metaphor of phase change. Whereas thermodynamics is a timeless science, nucleation brings in kinetics. Unrealized potential becomes activated through nucleation, and sudden and profound change can result. Likewise, the life, death, and resurrection of Christ provided that nucleating agent which converted the potential for change into actual change. By this abrupt and sudden action (καιροσ time, Greek for "fitting moment") the world underwent a transition to a new state. The outcomes of such sudden changes are often unexpected, for "surprise is inherent in nature" (Eaves and Gross 1992, 274).

The world remains today in a state with a tremendous potential for change. Nuclear warfare and environmental destruction remind us that this change can lead in the wrong directions. Christian hope, even in the midst of evil, keeps alive the ideal of positive change for the world. One of the lessons of nucleation science is that apparently small causes can have very large effects: a tiny solid particle can initiate the crystallization of a large body of water. The same is true in the world: the actions of individual men and women can have disproportionately large effects on nature and on humanity. As expressions of the Holy Spirit, these actions can move toward the establishment of the Kingdom of God.

Thus, through the metaphor of phase change we can see nature as a combination of the predictable and the unexpected. For the theist, this view combines a sense of the undergirding, continuous support of a creating and sustaining God with the sudden breakthroughs of God's grace that transform the world.

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