PHYSICS

The End of the World Is Flat

Raphael Bousso

Cycles of Time
An Extraordinary New View of the Universe

by Roger Penrose

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The universe began as a horizontal line: this much we knew. More recently, in a breathtaking experimental effort, we discovered that the world will end in a horizontal line. But if the end looks like the beginning, could it be that they are the same thing? Was our Big Bang the last gasp of a previous world? And will the death of our universe mark the birth of a new one? Such speculations are at the heart of *Cycles of Time*, the latest book by mathematical physicist Roger Penrose.

In 1905, Einstein created the special theory of relativity, fusing space and time into a single four-dimensional entity. A decade later, he formulated a theory of gravity, called general relativity. It posits that the geometry of four-dimensional space-time is curved by massive objects such as the Sun. The resulting shape, in turn, tells matter particles how to move. As long as the warping is small, this scheme provides the illusion of a gravitational "force" pulling Earth toward the Sun, whereas in fact our planet simply follows the straightest possible path through a curved geometry.

In many popular accounts, one finds this notion illustrated by a rubber sheet that is indented by the Sun, while Earth rolls around in the mold. But analogies of this kind are inadequate for visualizing many fascinating phenomena predicted by Einstein's theory. How are we to picture the Big Bang—the dense, hot initial state of our universe? How should one imagine the singularity at the center of a black hole? Black holes and cosmology are the settings in which general relativity truly comes into its own. But for half a century, physicists lacked powerful tools for visualizing them.

Enter the Penrose diagram. To picture the universe on a sheet of paper, it shrinks infinite regions of space and time to finite size. It zooms in on space-time singularities, such as the Big Bang, by stretching out the very early universe. But only a particular kind of distortion, a "conformal transformation," is permitted when passing from the real space-time to its depiction. This restriction ensures that the paths of light rays are faithfully represented. Nothing can travel faster than light, so no event can influence parts of the universe that are too remote for light rays to reach. We see only a portion of our own universe, a few billion light-years across, because light has only traveled for a few billion years since the universe began.

Because a Penrose diagram has the same light rays, it accurately captures the causal structure of the original, undistorted universe. By discarding an overwhelming wealth of detail, it allows the most important geometric features to become apparent. The presence of a black hole can be obscured by heaps of equations, but in a Penrose diagram, it is obvious. One glance suffices to recognize that the black hole singularity is not a point in space (a common misconception), but rather a moment of time that is eventually reached by all objects that enter the black hole. The Big Bang, too, is seen to be a moment of time; but it marks the beginning, not the end, of the classical space-time geometry. (Such initial or final moments of time can be represented by the horizontal lines alluded to at the beginning of this review.)

Penrose diagrams changed the way we think about curved space-time. The emphasis on global and causal structure liberated a stagnant field, ushering in a renaissance that stretched from Penrose's and Stephen Hawking's celebrated singularity theorems (*1*), through the discovery that black holes have thermodynamic properties (*2*, *3*), to the recognition of a completely general relation between classical space-time geometry and its quantum information content (*4*). Key signposts guiding our search for a quantum theory of gravity—Bekenstein entropy, Hawking radiation, and the holographic principle—owe a large debt to the methods pioneered by Penrose in the 1960s.

Our own universe exhibits a superficial similarity between the beginning of time and the infinite future: both look like horizontal lines in the Penrose diagram. As a result, we could stack one copy of the diagram on top of another, like so many wood blocks. A horizontal line separating two copies would seem to play a dual role as the future boundary of one universe and as the big bang of another. In *Cycles of Time*, Penrose asks us to take this whimsical picture seriously. In his viewpoint, the entire history of our universe is reduced to an "aeon," a mere segment in an infinite chain of beginnings and ends.

Penrose's proposal ascribes to his diagrams a universal status that they do not possess. Our world, in its rich phenomenology, is far more than a Penrose diagram. In nearly every respect, the beginning and the end of the observable universe are totally different.

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Near the Big Bang, particles were densely packed and very hot; but the universe will be empty and cold in the far future. The laws of physics contain many absolute scales that Penrose diagrams—designed as they are to distill out the causal structure—know nothing about. All hydrogen atoms, say, have the same fixed size in the real world; in a Penrose diagram, their size is arbitrary and changing.

Could it be that all absolute scales dissolve in the very early and late universe? Penrose suggests as much, in an attempt to lend the diagram a more fundamental role at least in these limits. But nucleosynthesis, say, occurs at a particular temperature in the early universe, and the cosmological constant leads to a particular expansion rate at late times. Many more examples teach us that the universe has always contained, and always will contain, information that its Penrose diagram lacks.

The cyclic proposal is motivated by a legitimate concern. The second law of thermodynamics tells us that entropy, a measure of disorder, is extremely unlikely to decrease. An egg may fall, break, and leave a mess on the floor, but chances are that the mess will not collect itself into an intact egg, which then jumps back on the table. Left to its own devices, matter will become more disordered over time until it reaches a state of maximum entropy, in which it spends the overwhelming fraction of its time. But the universe is not in such a state. The disorder in the universe has been increasing since the very earliest times, and it continues to grow today. We must understand why the universe began in an incredibly special state, so well ordered that 14 billion years later, the universe still has not reached maximum disorder.

Penrose is at his best when he explains this deep and beautiful mystery, and the book may be worth reading for this chapter alone. However, he compounds the shortcomings of his cyclic universe model when he argues that it can solve the low-entropy problem. At this point, another idea is introduced: like vacuum cleaners, black holes appear to reduce disorder by swallowing matter. By the end of one "aeon," Penrose argues, most matter has ended up in giant black holes. Very little entropy remains, and the next aeon can commence in perfect order.

The second law guarantees that a vacuum cleaner does not actually decrease the overall disorder; at best, it just shifts it around. In fact, the machine creates far more entropy than it destroys (for example, by heating up the air in the room). A black hole, it turns out, is not different. Penrose's assertion that black holes destroy entropy is flatly contradicted by "the generalized second law of thermodynamics" (*2*). Proposed by Jacob Bekenstein, this law maintains that disorder does not decrease even when disordered matter is lost into black holes. This is surprising at first, but no counterexample has ever been found. In fact, the law turned out to hold even in a situation that Bekenstein did not anticipate and that is relevant for Penrose's proposal. In 1974, Hawking discovered that black holes emit radiation (*3*). Over enormous time scales, a black hole will dissolve into a cloud of Hawking radiation and disappear. Careful calculations showed that the disorder of the Hawking cloud is always much greater than that of the matter that was destroyed when it fell into the black hole (*5*, *6*).

This is an example of the generalized second law at work. The processing of matter by black holes, far from imposing order, vastly increases the disorder. This result is hardly new or controversial, and it invalidates one of the central tenets of *Cycles of Time*. It is all the more puzzling that the result goes unmentioned in the book, especially as in places Penrose goes to great lengths to defend implausible assumptions—including some that fail to help his case. He supposes that information is lost in black holes, apparently in the belief that this would imply that black holes destroy disorder. But if this assumption were true, it would only make his task more hopeless. Information, in a very precise sense, is the opposite of disorder. Penrose's assumed information loss would introduce fundamental ignorance about the microscopic state of the Hawking cloud (thus increasing its "fine-grained entropy") while having no effect on the macroscopic disorder (the "coarse-grained entropy"), which increases in any case.

In the end, then, it is difficult to recommend *Cycles of Time*. Experts will already be familiar with the topics discussed in its stronger passages, such as the thermodynamic arrow of time and Penrose diagrams. And casual readers will have a hard time separating the wheat from the chaff.

References

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ECONOMICS

A Hopeful Vision of Food in Africa

Douglas Gollin

The New Harvest
Agricultural Innovation in Africa
by Calestous Juma
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Africa is a continent of farmers. South of the Sahara, about 60% of the economically active population makes a living from agriculture. Most of the continent's farms are extremely small, and productivity levels are very low.

For example, a 2003 survey of households in Mozambique found about 3.2 million farm households, cultivating an average of 1.4 hectares. A typical farm household (literally) scratches out a meager living from the soil: over 80% of the farms used no source of power other than hand tools and human labor; more than 90% used neither chemical fertilizers nor pesticides. Crop output is correspondingly low: Yields of the major food grains (maize, sorghum, and rice) are below one metric ton per hectare, leaving farm households with little surplus for sale to the market. For the grain crops, 75 to 95% of the output is consumed on the farms where it is produced (*1*).

To use a different metric of comparison (and a different country), a typical maize farmer in Kenya produces just under 1 kg of maize for every hour spent working on her farm (*2*). By contrast, a farmer in Iowa—working with far more capital and much better technology—can expect to produce over 1000 kg of maize per hour of labor.

In short, sub-Saharan Africa faces vast and daunting productivity deficits with respect to the rest of the world. Millions of people in the region are living and working in low-productivity, quasi-subsistence agriculture, with desperately low standards of living. Moreover, the data from recent years suggest that agriculture in Africa may actually be falling further behind rather than catching up.

In the face of this situation, it is easy to feel discouraged and pessimistic. Yet in *The New Harvest*, Calestous Juma offers a remarkably optimistic outlook for agriculture in Africa. Juma (a Kenyan scholar of sustainable development at Harvard University) argues that

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