Inflation and the Arrow of Time

Time, like a river, flows only from past to future; a British theorist thinks that cosmic inflation is the reason why

The "New Inflationary Scenario," an ambitious attempt to extrapolate the grand unified theories of particle physics into the earliest instants of the universe, has offered the first plausible explanation of such mysteries as the overall uniformity of matter in the universe, and perhaps even the origin of matter (*Science*, 28 January, p. 375). Recently, the British physicist Paul C. W. Davies of the University of Newcastle upon Tyne has pointed out that cosmic inflation might well solve another mystery: the asymmetry in the direction of time.* Although other physicists are not so sure, all agree that his idea is well worth pursuing.

It is a poignant fact of life that time rolls inexorably onward: what is done cannot be undone. But it is not immediately obvious *why* this should be so, since the fundamental laws of physics appear to be symmetric with respect to time. [The one exception, a tiny time asymmetry in the decay of neutral K-mesons, is rare and appears to have little relevance to the daily life of the universe.] If one could somehow make a movie of the atoms in, say, a scrambled egg, the jostle and turmoil would look pretty much the same whether the movie were run forwards or backwards.

But if the movie were filmed from the cook's point of view, it would look ridiculous running backwards. In real life one cannot unscramble an egg. Its atoms have been irretrievably mixed and randomized. A physicist would say that in its scrambled state the egg has a higher "entropy," which is a measure of randomness, and would point to the second law of thermodynamics, which formalizes the irreversibility of time as a statistical law: the world always goes from order to disorder, from low entropy to high entropy. The mystery of the asymmetry of time thus reduces to the question of how the universe got started in a highly ordered state.

Now at first it seems paradoxical to think of the Big Bang as highly ordered. The early universe was filled with a hot, homogeneous plasma of particles and radiation, which is about as *dis*ordered as things can get. But as Davies and many others have pointed out, thermodynamics in an expanding universe is subtle.† About 3 minutes after the creation, for example, the plasma had cooled enough for protons and neutrons to start fusing into heavier nuclei. Thermodynamically, everything should have wound up in tightly bound nuclei such as iron. But this did not happen because the fusion rates failed to keep up with the continuing expansion. The plasma fell out of thermodynamic equilibrium and the fusion process essentially stopped at helium. Thus, in a nuclear sense the universe is supercooled; its attempts to reach a more stable nuclear equilibrium via fusion reactions in stars is a major source of entropy increase. Among other things, the process provides the heat and energy for life on Earth.

More central to Davies argument, however, is another paradox. In the "low entropy" Big Bang, matter was widely dispersed. Yet in subsequent eons it cooled and clumped up into stars and galaxies, becoming increasingly more ordered. It seems like a gross violation of the second law. But it is not, and the resolution, says Davies, lies in the profound connections between gravity and thermodynamics discovered in the last decade.

The mystery is how the universe got started in a highly ordered state.

The link is plausible enough: there is a strong analogy between the irreversible clumping of matter under the influence of gravity and the irreversible increase of entropy dictated by thermodynamics. In the early 1970's, in fact, Jacob D. Bekenstein of the Ben-Gurion University suggested that in the most extreme case of matter crumpled into a black hole, the analogy could be made mathematically exact. His conjecture was proved in 1974 by the British theorist Stephen Hawking, who also proved the analogy was not just mathematical but real: quantum processes would allow the hole to radiate photons and other particles as if it were hot. In fact, a small black hole would rapidly explode.

Encouraged by this, says Davies, many physicists now believe that any gravitational field has a well-defined entropy: low when things are uniform, high when things are tightly clumped and when space, in the language of Einstein's general relativity, is chaotic and crumpled. Davies admits that no one has yet been able to formulate this concept precisely. But he nonetheless finds it plausible that the total entropy of the universe is the sum of gravitational entropy and matter entropy, with the inexorable clumping of the galaxies corresponding to the inexorable increase of that sum. The problem of the asymmetry of time, then, is to explain why the universe started out in a smooth state, when thermodynamics favored a highly crumpled space full of black holes.

The answer, says Davies, is cosmic inflation. Suppose that the universe did start out in a highly chaotic state, with some regions collapsing, others expanding, and black holes condensing and annihilating in bursts of Hawking radiation. Just by chance, says Davies, conditions within some small, hot patch of this cauldron would eventually send it over the threshold for the kind of "inflationary" expansion first predicted in 1980 by Alan H. Guth of the Massachusetts Institute of Technology. In essence, Guth's idea is that the interplay of grand unified particle theory and Einsteinian general relativity triggers a brief period of enormous outward pressure. The patch of space abruptly expands like a balloon, smoothing out as it goes.

Eventually, says Davies, the inflationary expansion dies away to the more modest rates of expansion called for in the standard Big Bang models. The inflated patch is ready to evolve into the universe we see around us today. But because it has been inflated, it starts as a smooth, homogeneous expanse with very low gravitational entropy.

Thus, Davies concludes, it is possible to postulate a universe that begins in an arbitrary, chaotic state and then gets "wound up" by the inflation. "The remaining history of the universe is the subsequent attempt to unwind by gravitational clumping (galaxies → stars → black holes) and nucleosynthesis (hydrogen → helium → iron). Together these two evolutionary chains account for all the observed macroscopic time asymmetry in the world and imprint upon our environment a distinct arrow of time."

—**M. Mitchell Waldrop**

*P. C. W. Davies, *Nature (London)* **301**, 398 (1983).
†S. Frautschi, *Science* **217**, 593 (1982).