weakly interacting dark-matter particles (if these stars are massive, as theory suggests but experiment has hitherto failed to confirm) are trapped in the stellar cores. Here the particles accumulate and annihilate, generating gamma rays and energetic particles that heat the stars.

The third age of the universe will be marked by proton decay. This is predicted by the theories of unification of the fundamental forces, although, again, no experimental confirmation yet exists. It is expected that protons rapidly decay and are created at the energy scale of grand unification ($\sim 10^{16}$ GeV). This hypothesis requires, however, that proton decay also occur at low energies—but very slowly. Indeed, the proton decay time is at least 10^{32} years. Nevertheless, after 10^{40} years have elapsed, one can be reasonably confident that all protons in the universe will have decayed. The only objects left will be black holes.

Even black holes do not last forever. Stephen Hawking predicted that the tidal forces near the event horizon of a black hole are so strong that pairs of virtual particles, which constitute the fabric of space and time, can be ripped apart. Virtual particles exist for so brief a time that the uncertainty principle tells us that conservation of energy is not violated, since the violations of energy conservation would be unobservable. The extreme curvature of space near a black hole is able to separate the virtual pairs into real particles, one of which escapes to infinity and thereby provides a channel for the black hole to evaporate. The smaller black holes will be the first to self-destruct, but eventually—after 10^{100} years—even the most massive black holes will have evaporated. The universe at this point will consist of the leftover waste from stars: radiation of very low frequency, neutrinos, and positrons and electrons.

Here in the Dark Era is where *The Five Ages of the Universe* offers some novel perspectives. The universe could be destined for boring senescence, but more extraordinary possibilities may await the intrepid spacetime explorer. The most remarkable of these is the possibility of a phase transition that may, literally, open new horizons.

The present universe acquired its characteristics through several phase transitions. The most remarkable of these, now generally accepted by cosmologists, was that of cosmic inflation. As it cooled after the Big Bang, the universe was caught in a state of false vacuum energy. It quantum-tunneled its way into the true vacuum, but during the brief period when the energy of the false vacuum dominated, at an epoch of about 10^{-35} seconds, the universe underwent a phase of exponential expansion.

This explains the present size of the universe and, indeed, the origin of its structure, through the seeding of inflated (in scale) quantum fluctuations. The energy field responsible for the inflationary phase transition is an example of a scalar field. Such fields are generally assumed to be omnipresent in high-energy physics, to account for the most basic properties of matters, such as the masses of the elementary particles. When the temperature of the universe drops below the energy of the field, a phase transition that can lead to the emergence of particle masses or to a period of inflationary expansion develops spontaneously.

The vacuum at present is characterized by a very low energy density. But a new scalar field could be lurking in the vacuum and be capable of triggering a future phase transition to a new vacuum state. Such a transition could spontaneously spawn exponentially inflating bubbles of new phase. The kinetic energy acquired would allow reheating to occur at the end of the phase transition, and our present universe would then be born or reborn. In effect, one can create new universes. Some even speculate that our universe is simply the largest and most dominant of these secondary universes. The long-term future of the universe may be rebirth.

Joseph I. Silk
Oxford University
Oxford, United Kingdom

The Touchstone of Life: Molecular Information, Cell Communication, and the Foundations of Life

Werner R. Loewenstein
Oxford U. P., New York, 1999. 366 pp. $30.00 hc ISBN 0-19-511828-6

The Touchstone of Life by Werner Loewenstein is an attempt by an eminent cellular biophysicist to explain nothing less than the origin of increasing "order" in living systems, as they have evolved from simple self replicating systems to highly complex multicellular organisms. Loewenstein is haunted by the increasing "information content" of biological systems and compares this to the action of a Maxwell's demon, that little, all-knowing devil at the gate who decides who shall pass from one side of a container to another.

At first glance, such a demon seems to violate the Second Law of thermodynamics, but there are many ways to see directly and quantitatively, at the near-freshman-physics level, why such a demon can't work. I am sure that Loewenstein understands that Maxwell's demon can't work when analyzed carefully and physically. But he takes quite a different tack: His book is full of biological demons, representing the proteins that pump ions preferentially across membranes or read DNA sequences and so on.

Rather than examine these "demons" physically to see how in fact they work at the atomic level, consuming energy in the process, he takes a far more abstract and philosophical viewpoint and states that the information entropy increase that the demon uses to sort things must exactly cancel the configurational entropy lost when molecules are separated. Loewenstein basically modifies the free energy terms of H, T and S that we all plow through in a thermodynamics course and adds an information entropy term that exactly cancels out configurational entropy terms.

With this foray into information theory, we are then launched into much philosophical musings about the circus of life and a lot of really florid writing. Here is an example: "The nascent molecules suckled photons, as it were. That suckling was stepped up when the larger organic molecules emerged and, while eventually there would be more mature ways to bring through the organization entropy quid pro quos, it became a habit from which living beings would never be weaned. But it truly began in earnest with the advent of the cybernetic loop. Then, the photon quanta were sucked nonstop into a circulating flow of information . . . ." This is more about the private life of these molecules than I really want to know, and I am not sure we really learn anything from this exaggerated style of writing. I am a lot more comfortable viewing sunlight as an energy source than as an information source.

The problem with this book is that, behind all the philosophy and demons and circuses, I really didn't learn about how in fact these molecules physically really work. In some respects, molecular biology has turned into a miracle show; we understand a great deal about *what* is happening in biology and a fair amount of *why*, but *how* it happens remains pretty much a mystery. This is a different kind of understanding from what we got in freshman physics; it isn't quantitative model building and quantitative model testing so much as it is deductive and based on empirical analysis of large information data bases. That seems to be what Loewenstein is saying: the mere fact that information is lost is sufficient to explain what happens; don't bother me with the details. Who knows! Maybe this is the best way to approach biological complexity, but I hope not.

In the end I think such an approach must fail. Lord Kelvin said that when you could put a number on a quantity than you really had some understanding. Handwaving about information theory and demons without a quantitative model to test must lead to a dead end. This became clear to me by the end of this book, when the subject arose of how the human mind works. I was shocked to find that an uncritical discussion of the quantum-coherence-in-the-mind nonsense of Hans Froehlich played a central role in the discussion. Any basic analysis of wavefunctions, correlation lengths and coherence times instantly destroys this model, but of course if your science has no numbers, there is no test of models.

This book is an amusing read and it will send you running to John Pierce's excellent *An Introduction to Information Theory* (Dover, 1980) to try and figure out if you really have been missing something in your understanding of statistical mechanics, but I just can't take it seriously. Long live freshman physics! When we can explain things at the freshman-physics level, with real numbers, we truly understand things.

ROBERT H. AUSTIN
Princeton University
Princeton, New Jersey

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