PHYSICS

Finding the time

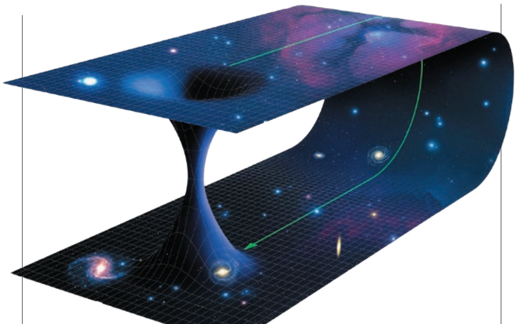
Andrew Jaffe takes the measure of two books on the tangled concept of the temporal.

What is time? If you're a practising physicist, it's a quantity in your equations, *t*. This is the variable that you use for one of the four dimensions of the manifold of space-time, the term coined by mathematician Hermann Minkowski after Albert Einstein's theories of relativity began to show that time and space are fungible. And yet we can move freely back and forth in space but not in time. Why?

In *Time Travel*, science writer James Gleick reviews the science of time by focusing (mostly) on the science fiction of time travel. He starts from, and often returns to, H. G. Wells's *The Time Machine*, which predates Einstein's 1905 special theory of relativity by a decade. It's a pleasurable romp over Wells's fourth dimension and polished Victorian machinery; 'golden age' science-fiction authors such as Isaac Asimov, who provided the templates for modern treatments of time travel; and the Doctor Who franchise (A. Jaffe *Nature* **502,** 620–622; 2013). Gleick also explores more highbrow offerings from writers such as David Foster Wallace and Jorge Luis Borges (who envisaged time as a "Garden of Forking Paths"), and filmmaker Chris Marker, whose 1962 sci-fi short *La Jetée* inspired 1995 time-travel noir *12 Monkeys*.

Gleick doesn't exactly wear his knowledge lightly, but he does cram a lot in, especially in discussions of the physics. Einstein's 1915 general theory of relativity seems to allow for "closed timelike curves", paths that start at one place and time, and end at exactly the same place and time. Unfortunately, actually creating space-time with such a curve — that is, a time machine — may be impossible, an idea formulated in Stephen Hawking's "chronology protection conjecture". In this, the Universe conspires to make time machines impossible to build: they require physically impossible states of matter, or their creation may also generate a black hole around the machine, making it impossible to access.

But even the normal perceived flow of time in one direction is mysterious. Most of the microscopic equations of physics have a fundamental symmetry: they can't tell whether time is moving forwards or backwards (mathematically, they look identical if we replace t with $-t$). But this is not how we experience time. We move inexorably from past to future; we remember the past and have no direct knowledge of the future. One exception to time-reversal symmetry is thermodynamics, whose second law says that entropy always increases with time. Astronomer



MARK GARLICK/SPL

A 'wormhole' — a favourite time-travel device.

Arthur Eddington opined that this alone is responsible for the 'arrow of time'. The problem is that the second law is not really about physics, but probability — and hence knowledge. We know less about the details of a high-entropy system than a low-entropy one, so it's harder to extract useful work.

The symmetry of time is also broken in quantum mechanics, which describes a physical system by its wavefunction, but gives us probabilities, not definite results. When we make a quantum measurement, we sometimes say that the wavefunction collapses, a process that has only one direction. But this is about knowledge, too, in contemporary ways of understanding quantum mechanics such as the many-worlds interpretation — the idea that every possible outcome exists out there in the multiverse. When we make a measurement, we gain information about the system.

Gleick spends some pages on the 'problem of now', the question of how the equations of physics seem to give us a Universe in which time isn't just one of four space-time dimensions. Instead, it is special: why do we always live at a specific moment, only remembering the past and waiting for the future? The issue nags at many physicists, including me. Sometimes, I'm convinced that 'now' is a non-problem. Once quantum mechanics and thermodynamics have given time a direction, 'now' isn't physics, but a combination of time's arrow with psychology and physiology. The past is what is encoded in our memories. To a rock, an electron or a galaxy, there is no now. But occasionally I wonder whether this is sufficient.

Physicist Richard Muller also seems exercised by this conundrum. His *Now* attempts to lay out a solution. He starts with a pop-science introduction to the required physics: the broad theories of relativity and quantum mechanics, and the specific roles of cosmology and particle physics in our Universe, such as those of the Higgs boson and its mass-giving field. His introductions to modern physics are probably too technical for most lay readers, despite relegating most of the harder maths to a series of appendices.

Unfortunately, after dispensing with physics, Muller delves into philosophy, a discussion that hardly rises above the university-bar level. For example, he takes for granted that free will is not compatible with determinism. This has been debunked in philosophy, for instance by Daniel Dennett in the 1991 *Consciousness Explained* (Little, Brown), or this year by Sean Carroll in *The Big Picture* (R. P. Crease *Nature* **533,** 34; 2016). Instead, Muller opts for the manifestly non-scientific idea of a non-physical soul with causal powers over the quantum-mechanical wavefunction.

This is pretty far-out, but is just a side note. Muller's main thesis is that the expansion of the Universe "is continually creating not only new space but new time". That is a good soundbite, but cosmologists debate whether the starting point — the idea of creating new space — is itself meaningful. Since writing the book, Muller has expanded on his ideas more mathematically, and applied them to this year's observations of gravitational waves (R. A. Muller and S. Maguire. Preprint at http://arxiv.org/abs/1606.07975; 2016). Kudos to him for proposing an idea that may be testable. Very few popular or professional physics books bother to make an argument, summarizing the state of the art instead. Unfortunately, I don't buy Muller's argument: whether or not 'now' is a non-problem, Muller's idea is a non-solution in my view.

Both Gleick and Muller want us to realize that time is central to our experience — that having a now is what constitutes having an experience at all. Even if travelling into the past is a fantasy, the physics of time encompasses almost everything that physicists study. Perhaps understanding its flow will give us a more complete picture of our changing Universe. ■

Time Travel: A History
JAMES GLEICK
Pantheon: 2016.

Now: The Physics of Time
RICHARD A. MULLER
W. W. Norton: 2016.

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