are led away to their doom".

He says what you wouldn't expect; if Dyson has a pattern, perhaps it is contrariety. He prefers the students at Haverford College, a liberal-arts university in Pennsylvania — who are "ostentatiously ill-dressed, uncombed, and unwashed" — to Princeton's "pampered" ones. He contradicts himself. His wartime job at the UK Royal Air Force's Bomber Command, analysing the effect of Allied firebombing on German cities, left him with a "permanently bad conscience". Yet he understood the joy of German sailors who torpedoed Allied fuel tankers because he felt "elation" when the firebombing succeeded.

"All these adventures in this strange new world are still unreal to me."

In the late 1950s, he worked with the defence contractor General Atomic in La Jolla, California, on a project he thought would be "legendary": a spaceship called Orion, ill-advisedly powered by nuclear explosions. Because building it required nuclear testing, he publicly opposed the Nuclear Test Ban Treaty; after Orion was defunded, he supported the treaty. Later, he became president of the anti-nuclear-proliferation Federation of American Scientists. He proposed the 'no first use' policy on nuclear weapons, while admiring his theoretical-physicist friend Edward Teller for standing against the treaty. Dyson's contradictions might seem confusing, but I can hear him politely and methodically explaining the rationality of seeing reality from different reference frames, of holding mutually opposing views and of being free to change one's mind.

The one Dysonian pattern for which the letters hold unequivocal evidence is delight. He uses the word often and invokes it even more: "Today I discovered a little theorem which gave me some intense moments of pleasure. It is beautiful and fell into my hand like a jewel from the sky." In the book's last letter, he writes to his sister about being robbed and hit on the head. Preparing to die, he notices the sunlight on the bushes and thinks, "life has been good to me and this death is also good, with the bright sun and the green bushes".

Maybe with some people, you don't look for patterns. You just enjoy their multivariate company. ■

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Niels Bohr (left) with Albert Einstein in the late 1920s, when quantum mechanics was in its infancy.

EMILIO SEGRE VISUAL ARCHIVES/AIP/SPL

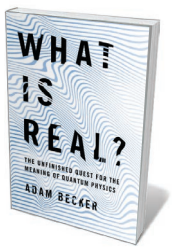
PHYSICS

Quantum-theory wars

Ramin Skibba explores a history of unresolved questions beyond the Copenhagen interpretation.

All hell broke loose in physics some 90 years ago. Quantum theory emerged — partly in heated clashes between Albert Einstein and Niels Bohr. It posed a challenge to the very nature of science, and arguably continues to do so, by severely straining the relationship between theory and the nature of reality. Adam Becker, a science writer and astrophysicist, explores this tangled tale in *What Is Real?*.

Becker questions the hegemony of the Copenhagen interpretation of quantum mechanics. Propounded by Bohr and Werner Heisenberg in the 1920s, this theory holds that physical systems have only probabilities, rather than specific properties, until they're measured. Becker argues that trying to parse how this interpretation reflects the world we live in is an exercise in opacity. Showing that the evolution of science is affected by historical events — including sociological, cultural, political and economic factors — he explores alternative explanations. Had events played out differently in the 1920s, he asserts, our view of physics might be very different.



What Is Real?: The Unfinished Quest for the Meaning of Quantum Physics
ADAM BECKER
Basic: 2018.

Becker lingers on the 1927 Solvay Conference in Brussels, where 29 brilliant scientists gathered to discuss the fledgling quantum theory. Here, the disagreements between Bohr, Einstein and others, including Erwin Schrödinger and Louis de Broglie, came to a head. Whereas Bohr proposed that entities (such as electrons) had only probabilities if

they weren't observed, Einstein argued that they had independent reality, prompting his famous claim that "God does not play dice". Years later, he added a gloss: "What we call science has the sole purpose of determining what is." Suddenly, scientific realism — the idea that confirmed scientific theories roughly reflect reality — was at stake.

Quantum phenomena were phenomenally baffling to many. First was wave–particle duality, in which light can act as particles and particles such as electrons interfere like light waves. According to Bohr, a system behaves as a wave or a particle depending on context, but you cannot predict which it will do.

Second, Heisenberg showed that uncertainty, for instance about a particle's position and momentum, is hard-wired into physics. Third, Bohr argued that we could have only probabilistic knowledge of a system: in Schrödinger's thought experiment, a cat in a box is both dead and alive until it is seen. Fourth, particles can become entangled. For example, two particles might have opposite spins, no matter how far apart they are: if you measure one to be spin up, you instantly know that the other is spin down. (Einstein called this "spooky action at a distance".)

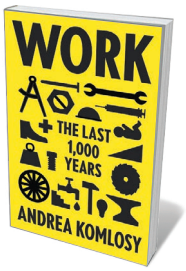
Becker explains how these observations challenge locality, causality and determinism. In the classical world of billiard balls, projectiles and apples falling from trees, they were never problems.

Sifting through the history, Becker shows how Bohr, as an anti-realist, brought to his side many rising physicists, including Heisenberg, Wolfgang Pauli and Max Born. Einstein, however, persistently argued that the Copenhagen interpretation was incomplete. He conjectured that there might be hidden variables or processes underlying quantum phenomena; or perhaps 'pilot waves', proposed by de Broglie, govern the behaviour of particles. In 1932, mathematician John von Neumann produced a proof that there could be no hidden variables in quantum mechanics. Although mathematically correct, it was revealed to be flawed decades later. But the damage had been done: the potentially viable alternatives conceived by Einstein and de Broglie remained relatively unexplored. The Copenhagen interpretation had taken hold by the 1930s, and textbooks today state that Bohr's view 'won'.

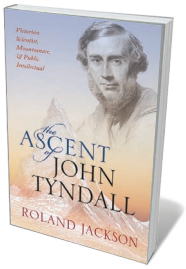
Thus, the Solvay Conference can be seen as a stand-off between two mathematically equivalent but fundamentally different paradigms: Bohr's instrumentalist view of quantum physics and Einstein's realist one. In science, a dominant paradigm determines which experiments are done, how they're interpreted and what kind of path a research programme follows.

But what if a field picks the wrong paradigm? Becker shows how, in the 1950s and 1960s, a handful of physicists dusted off the ▶

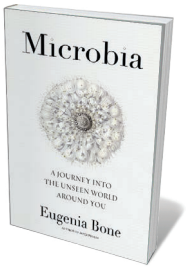
Books in brief



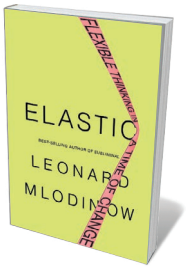
Work: The Last 1,000 Years
Andrea Komlosy, trans. Jacob K. Watson & Loren Balhorn VERSO *(2018)*
Employment outside the home became the globally dominant form of work only after 1900. Yet in policy and discourse, it has eclipsed older, more informal modes of production. Social historian Andrea Komlosy probes the joins between them in this sweeping chronicle, from 1250 — the dawn of globalization and urbanization — to today, when international corporations threaten labour standards. This is a book teeming with insights, from the contempt for manual labour in ancient Greece to the historical tendency for all kinds of subsistence tasks to be "housewife-ized" into unpaid domestic labour.



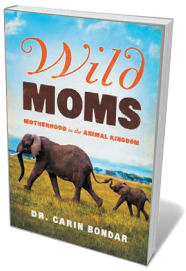
The Ascent of John Tyndall
Roland Jackson OXFORD UNIVERSITY PRESS *(2018)*
A leading light in climate science, germ theory and magnetism, Victorian researcher John Tyndall seemed a man for all sciences. He discovered the greenhouse effect and why the sky is blue, and as a public intellectual, hobnobbed with physicists Michael Faraday and Hermann von Helmholtz, and poet Alfred Tennyson. This splendid monument of a biography by Roland Jackson tracks Tyndall's rise from rural Ireland to laboratorial glory days in Britain and Europe. The experimentalist's obscurity now, Jackson avers, may be down in part to his death in 1893: he just missed the era of relativity and the quantum.



Microbia
Eugenia Bone RODALE *(2018)*
At the age of 55, journalist Eugenia Bone returned to university to take a microbiology course, reasoning that "humility is the entry point for studying nature". The microbial matrix of life came into focus. Bone's is an exquisitely observant, often amusing voyage from the origins of life to antibiotic resistance, punctuated by scientific revelations. (The compound geosmin, produced by *Streptomyces* bacteria, gives soil its sweet smell; bacteria nucleate rain; a quadrillion microbes pack part of a cow's stomach.) The devil's in the detail, Bone finds, but what enchants is the connectivity of this 'hidden' ocean.



Elastic: Flexible Thinking in a Constantly Changing World
Leonard Mlodinow PANTHEON *(2018)*
Physicist Leonard Mlodinow revels in the neuroscientific. Here he extends his explorations with an in-depth study of agile creative thinking in a hectic age. Among the psychological factors Mlodinow isolates are a yen for novelty, and the capacity to reconcile diverse ideas. He plunges deep into the human brain, marshalling compelling research both on brain basics and on outlier issues such as mental blocks. Perhaps most gripping is his take on the "default network" — the brain structures that govern richly creative activities such as daydreaming, the "dialogue we have with ourselves".



Wild Moms
Carin Bondar PEGASUS *(2018)*
Biologist and broadcaster Carin Bondar's tour of the vagaries of motherhood in the animal kingdom is a thrills-and-spills survey, from brood parasitism to cooperative breeding. The diversity of evolutionary solutions to maternality is mind-bending. We learn, for instance, how baby koalas ingest their mothers' faeces to inoculate their gut microbiomes, and that female gastric-brooding frogs vomited up their froglets. Ultimately, however, this is less a synthesized narrative than a biological litany. **Barbara Kiser**

theories of Einstein and de Broglie and turned them into a fully fledged interpretation capable of shaking up the status quo. David Bohm argued that particles in quantum systems existed whether observed or not, and that they have predictable positions and motions determined by pilot waves. John Bell then showed that Einstein's concerns about locality and incompleteness in the Copenhagen interpretation were valid. It was he who refuted von Neumann's proof by revealing that it ruled out only a narrow class of hidden-variables theories.

"Becker reminds us that we need humility as we investigate the myriad interpretations that explain the same data."

The scientific community greeted Bohm's ideas coolly. A former mentor, J. Robert Oppenheimer, said: "if we cannot disprove Bohm, then we must agree to ignore him". And, as Becker shows, Bohm's leftist views led to an appearance before the House Un-American Activities Committee, and subsequent ostracization.

Bohm's contemporary, physicist Hugh Everett, delivered another challenge to the Copenhagen interpretation. In 1957, Everett set out to resolve the 'measurement problem' in quantum theory — the contradiction between the probabilistic nature of particles at the quantum level and their 'collapse', when measured, into one state at the macroscopic level.

Everett's many-worlds interpretation posited no collapse. Instead, probabilities bifurcate at the moment of measurement into parallel universes — such as one in which Schrödinger's cat is alive and another in which it's dead. Although an infinite number of untestable universes seems unscientific to some, many physicists today view the theory as important.

The book has a few minor shortcomings. Becker gives too much space to recent applications building on Bell's research, and too little to new developments in the philosophy of science. Yet he, like cosmologist Sean Carroll in his 2016 *The Big Picture* (R. P. Crease *Nature* **533,** 34; 2016), does make an explicit case for the importance of philosophy. That's a key call, with influential scientists such as Neil deGrasse Tyson dismissing the discipline as a waste of time.

What Is Real? is an argument for keeping an open mind. Becker reminds us that we need humility as we investigate the myriad interpretations and narratives that explain the same data. ■

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A Pan Am shuttle prepares to dock at the international *Space Station V* in this classic scene from the film.

IN RETROSPECT

2001: A Space Odyssey

Fifty years on, the masterful science-fiction film looks more prophetic than ever, reflects **Piers Bizony**.

In 1968, film-maker Stanley Kubrick and his screenwriting colleague, science-fiction author Arthur C. Clarke, presented *2001: A Space Odyssey*. Half a century later, this unprecedentedly detailed speculation about our place in the cosmos and our evolving relationship with technology is regarded as one of the great landmarks in cinema.

The influence of *2001* on the design of subsequent space-film hardware and special effects has been pervasive. However, in terms of artistic and philosophical bravura, it has been a harder act to follow. In 2007, director Ridley Scott (of *Blade Runner* and *Alien* fame) told a Venice Film Festival audience: "After *2001*, science fiction is dead."

2001: A Space Odyssey
DIRECTOR: STANLEY KUBRICK; CO-WRITER: ARTHUR C. CLARKE
Metro-Goldwyn-Mayer: 1968.

The narrative was ambitious, to say the least. Prehistoric apemen have a mind-altering encounter with an alien black monolith. Four million years later, a giant spacecraft is sent to Jupiter on a mysterious mission. On board are two astronauts, three hibernating scientists and a seemingly sentient computer, HAL 9000. Hovering above Jupiter, another monolith waits.

Monoliths aside, *2001* was prescient in almost all its detailed predictions of