

stricter sense.) Some are common misconceptions, *e.g.*, Special Relativity (SR) cannot deal with acceleration (p. 157) — the main difference is that SR is restricted to (flat) Minkowski space and General Relativity (GR) allows for curved space–time (to be sure, gravity curves space–time, and the Equivalence Principle relates acceleration and gravity, but nonetheless SR can describe acceleration). It is at least implied that Schwarzschild died on the battlefield; he died in hospital, away from the front, and of an auto-immune disease, not war wounds (p. 160). (She does get the history of the term ‘black hole’ correct, crediting Dicke and not Wheeler, p. 160.) Bell wasn’t yet Bell Burnell when she discovered pulsars (p. 172). The last sentence in the first paragraph of the last section in the chapter on neutron stars (p. 182) states “Sadly, Bell Burnell is less known for her scientific breakthrough than for the controversy that surrounds it.” That might well be true, but I wonder if devoting eight paragraphs to said controversy will improve the situation. At the risk of doing the same, I note that the actual discussion agrees with my assessment and correctly differentiates the question of whether she should have received a share of the Nobel Prize (including placing the decision in the context of the time and Bell Burnell’s own take on the matter) from the silly reporting by many journalists at the time. While GR indeed describes changes in the gravitational field propagating at the speed of light, not all such changes correspond to gravitational waves as usually thought of (p. 189). Since this is the third book in which I have noticed it, the idea that astronomers can somehow *measure* the radial velocity of extragalactic objects is becoming a common misconception (p. 248).

Others are more bizarre: Drake’s choice of 1679 pixels for his Arecibo message was due to it being the product of the two primes 23 and 73, but of course 1679 itself is not prime (p. 235). The description of the Hubble law is at best confused (p. 247). It is at least strongly implied that Einstein was aware of Friedmann’s work (which was done some years later) when the former added the cosmological constant in order to have a static universe (p. 248). The history of dark matter is at best too brief. P. 263: “Dark energy was proposed in the 1990s, when observations of distant supernovae revealed that the expansion of the Universe is not slowing down as expected, but accelerating.” That is literally true, but it was not *first* proposed (which seems to be implied) then, and though the *term* ‘dark energy’ was proposed then the idea is older. (Sometimes ‘dark energy’ is used to contrast it with a cosmological constant, the former having an equation of state other than $p = -\rho$ and/or the value or even the equation of state changing with time, though none of those were needed in the 1990s and probably none is needed today.) Further discussion of supernova cosmology is at best muddled (pp. 278–279).

However, most of the mistakes are related to cosmology, with which only a small part of the book is concerned, and are rather common, both of which are true of many books reviewed in these pages. I think that it is important to mention them, but at the same time the space devoted to them in this review exaggerates their importance. The rest of the book is not only (as far as I can tell) technically correct, but is well written and conveys the author’s love of radio astronomy, a topic which should get much more attention in books at this level; perhaps this book can be a step in that direction. I certainly enjoyed reading it and, despite being an honorary radio astronomer, learned many new things. — PHILLIP HELBIG.

On Time: The Physics That Makes the Universe Tick, by Jim Al-Khalili (Princeton University Press), 2026. Pp. 359, 24 × 16 cm. Price £28/\$32 (hardbound; ISBN 978 0 691 26703 6).

Al-Khalili is a well-known popular-science writer and presenter on radio and television with a background in theoretical nuclear physics; he is a professor of physics at the University of Surrey, where he also holds a chair in the public engagement of science. This is the first book by him that I have read. I’ve read many books on the nature of time and reviewed some in these pages, though they were usually more technical and/or edited volumes with several authors. In particular, this book — with an important exception mentioned below —

could be seen as something like a popular-science version of a book¹ reviewed² in the 2026 August issue of this *Magazine*. It's more than just a typical popular-science book, though, as some of its contents reflect research done by Al-Khalili and colleagues in the context of a large research grant, in an area (the philosophy of time) somewhat removed from his earlier specialization. While there are many popular-science books on time itself (including an excellent one³ reviewed in these pages⁴), there are few on the philosophy of time.

The preface notes that the book is concerned with physical time, not “mystic or poetic notions”. That does not exclude our perception of time, ‘manifest time’. That and basic questions are discussed in the introduction, such as whether time is an illusion, whether (and if so how) it flows, whether it is continuous, why it has a direction, and so on. The two philosophical problems of time are why we perceive it to flow and why we perceive the past to be different from the future, given that those facts aren't obvious from the equations of physics. The two physical problems are the connection between the coordinate time of classical or quantum physics and the time which is part of space–time in relativity, and reconciling time-symmetric dynamical equations with the irreversibility of thermodynamics.

There are so many concepts involving (the philosophy of) time that some structure is needed. The four parts of the book provide some of that, reflecting time as a label, as a dimension, as an arrow, and the reality of time. The first, with four chapters, discusses the basic concept of time as a coordinate which indicates when something happened, as in Newtonian or quantum mechanics, and how it is measured. The philosophy of time becomes important when psychological time and the question of free will *versus* determinism are discussed. The second, with five chapters, covers Special and General Relativity, including cosmological time, the idea of the block Universe, and the fact that ‘now’ is not clearly defined in a relativistic context. The third (four chapters) discusses various arrows of time: psychological, entropy, causal, cosmological, quantum, *etc.* Al-Khalili sees statistical mechanics on an equal footing with Quantum Mechanics (or dynamical physical equations in general) and Relativity with respect to its role in the foundations of physics, and there is a good discussion of various types of entropy, Loschmidt's paradox, and so on.

The closest thing to a consensus on the topic of the arrow of time is that all arrows of time are ultimately derived from the cosmological arrow of time, which is due to the Universe having started in a state of very low entropy, which is difficult to explain. (One might think that radiation would have a high entropy; that is true in the absence of gravity, but with gravity the high-entropy state is with everything in black holes.) Thus, the importance of the Past Hypothesis, which is just a statement of that fact, without explanation. Most discussions, at least most I am familiar with, are concerned with ‘traditional’ entropy (*e.g.*, that of particles of matter or radiation) or gravitational entropy. Al-Khalili emphasizes the importance of a third type of entropy, namely that connected with nuclear fusion. It is the increase of entropy as the result of fusion which ultimately responsible for most entropy-related phenomena. Since the possibility of such fusion is merely one of many aspects dependent on the fine-tuning of our Universe (*e.g.*, ref. 5 and references therein, reviewed⁷ in these pages), Al-Khalili also introduces the interesting twist that no extra Past Hypothesis is actually needed; it is merely one aspect of the fine-tuning of our Universe for life, which is hard to dispute, though there is disagreement about its explanation (*e.g.*, refs. 5,6). Considering that many have deemed the problem of the origin of the low-entropy Big Bang the most important outstanding problem in physics, such a simple explanation — which I haven't seen anywhere else — is at least very interesting.* With the beginning out of the way, the reader is then presented with various ideas about a possible end of time. Contemplating extremely long periods of time leads to the idea of ‘Boltzmann brains’, conscious observers which arise due to fluctuations. Whatever one thinks of them (the author apparently doesn't think much of the idea), as a serious area

*Al-Khalili does point out what are the author's own ideas and what is his summary of the field, always something worth doing when a popular-science book includes the former as well as the latter.

of research I would have liked to have had a bit more discussion than the short shrift they are given here.

The fourth part is intended to convince the reader that time is real, with one chapter discussing the idea of time as an emergent concept within the context of quantum gravity, and the other introducing Al-Khalili's concept of entanglement entropy. The interrelated concepts of quantum measurement, entanglement, and decoherence are discussed. It is, correctly, pointed out that entanglement is not limited to the special cases we read about in laboratory experiments, but is actually the rule, and that decoherence is extremely important. The two chestnuts that the laws of physics are time-symmetric and that entropy almost always increases both apply only to isolated systems. Of course, no system in the Universe is truly isolated, but that is not appreciated enough. I remember John Barrow's example of aiming a cue ball at the other 15 balls at the start of a game of pool with the maximum precision allowed by the uncertainty principle; after just 15 collisions the uncertainty in the balls' positions would be larger than the size of the table. We are reminded of a similar but more impressive argument due to Michael Berry already mentioned in Chapter 4: Take the classic molecules-in-a-box thought experiment from a typical discussion of statistical physics, which is alone in the Universe except for one electron at the limit of the observable Universe — but we don't know in which direction. Even if we could measure the position and momentum of each molecule in the box *exactly*, after 50 collisions, *i.e.*, within a tiny fraction of a microsecond, we would lose predictability due to our lack of knowledge of the position of the electron. With the smallest imaginable perturbation having such an effect so quickly, no system can be described as even approximately isolated, thus giving great importance to decoherence. The irreversibility of quantum decoherence, together with an initially non-entangled Universe is thus the ultimate source of arrows of time. The fly in the ointment is that a new Past Hypothesis regarding a non-entangled Big Bang seems to be needed, since fine-tuning doesn't seem to explain it as it does the traditional Past Hypothesis. (After such heavy going, the bonus chapter on time travel after the afterword is almost light relief! There is nothing novel here, but it is included because it seems to belong in a book on time.)

As with many books I've reviewed, there are a few blunders relating to cosmology, but fewer and more harmless than is usually the case and not important for the main narrative. There are a few black-and-white drawings scattered throughout the book and a few footnotes; the nine pages of small-print endnotes after the acknowledgements are references — unusual for a popular-science book, but appreciated. The two pages (also in small print) of about 50 suggestions for further reading are particularly interesting: I've reviewed some of the books, just read others, some were already on my ever-growing list of books to read, others I've added to it. A nine-page small-print index and a note on the type end the book. The book is a nice combination of the familiar and the new, well researched, and thought-provoking; anyone interested in time should find the time to read it. — PHILLIP HELBIG.

References

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- (3) C. Orzel, *A Brief History of Timekeeping: The Science of Marking Time, from Stonehenge to Atomic Clocks* (One World), 2022.
- (4) P. Helbig, *The Observatory*, **142**, 288, 2022.
- (5) G. F. Lewis & L. A. Barnes, *A Fortunate Universe: Life in a Finely Tuned Cosmos* (Cambridge University Press, Cambridge), 2017.
- (6) P. Helbig, *Found. Phys.*, **16**, 93, 2023.
- (7) P. Helbig, *The Observatory*, **137**, 243,