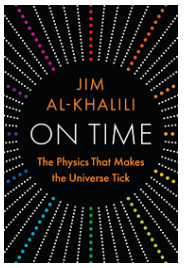
Jim Al-Khalili, **On time**. The physics that makes the universe tick, Princeton University Press, 2026, 360 p., isbn: 978 069126703 6 (hbk)





Jim Al-Khalili

Al-Khalili is a physicist and science communicator. He features regularly on BBC radio and TV and he has published several books on paradoxes, quantum theory, physics, and history. I liked this book in particular because he explored deeply the enigmatic nature of time: mathematics does not seem to explain the arrow if time because formulas are time-symmetric. Einstein introduced it as a fourth dimension, but it definitely is different from the three space dimensions. And our personal experience is that it runs faster when we have fun, and slower when we are waiting. Older people have the feeling that times runs faster than when they were young. So is time something people generate in their brain, or does time exist independently of our perception? Is it infinite and has it a beginning and an end? All questions considered in psychology and philosophy, but where we hope that science can give an answer, So far we are still looking for accurate models of the human brain and we are missing the unification of quantum theory and Einstein's (general) relativity theory that should become a unified theory of everything (ToE). Where do we come from and what future is our cosmos running into? In other words, time touches on all the big questions. And Al Khalili investigates all their possible answers and gives his own opinion on which answers could be the right ones and which ones to exclude.

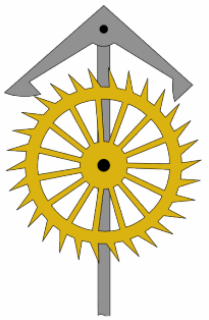
Reading this book is a mind blowing experience that makes it painfully clear that there is so much that we still do not know, and although there is not so much explicit mathematics, the mathematicians are figuring in the background from Greek philosophers over Laplace and Newton, to Einstein, Hawking, and Penrose. Eventually quantum gravity and the ToE that should hold both for the extremely small and the extremely large will obly be solved when the appropriate mathematical framework will be developed.

The first chapter is an exploration of the problem or rather the multitide of problems. While it is clear that in 3D space all the positions do exist simultaneously and we can move from one position to another. If we leave a room, we know it is still there and we can return if we want to. But that is not possible for time. We con only undergo time. So, do all time instances exist when we are not living it? The past is gone, the future not here yet. Does time exist physically, or is it something that emerges from our experiences, like temperature is emerging from the activity of atoms in a material? We experience time as either the past which we know (remember) partially, and we can expect what's going to happen in the future, but we do not know for certain. It does not exist yet or does it? And what is "now"? Is it a cut between the past and the future? We all have an intuitive idea what is "now", how long it remains "now"? Philosophers distinguish between *eternalists* who claim that time is real and all time instances exist always, or *presentists* who claim that only the present exists and that time (and its consequences like change, causality, etc.) is emergent. Think of Zeno's paradoxes of motion. And there is of course the arrow of time: does time flow by while we are static, or is time static like space and are we moving through time like we move through space at a rate that we cannot control neither in direction nor in speed. Different arguments have been given to explain the arrow of time, but none is absolute, And finally, is time continuous or is a sequence of time-quanta?

I can give you Khalili's answers to some of these questions. This is not a spoiler because he also gives them at the beginning of the book: The time flowing is an illusion; time is real, i.e., not just an emmerging experience; and the arrow of time has many appearences, but there is a "master arrow" given by nature which is generated by quantum decoherence which relates to the *past hypothesis* (i.e. time started at a moment of extremely low entropy, which is the Big Bang ($13,8 \times 10^9$ years ago), and entropy has ever increased since).

The full explanation and his arguments for these answers he gives in the subsequent chapters

subdivided into four parts and a bonus chapter in which he discusses different aspects of time. The first part is the time t as it appears in formulas, i.e., as a parameter or a label. This chapter has a strong historical component describing instruments to measure time, i.e., methods to capture change, from solar time-keeping over sand or water clocks to clocks with a pendulum and a verge escapement; introduction of the GMT, quartz crystals, atomic clocks and the most recent optical lattice clocks with a resolution of 1 attosecond (10^{-18} sec) with a possible drift of 1 sec in 30×10^9 years. And yet, this is still far away from the Planck time ($15,39 \times 0^{-44}$ sec), the smallest meaningful time interval. It relates to the Planck length which is the distance traveled by light in 1 sec (1.61×10^{-35} m). Beyond these limits, time and space make no sense any more. Chapter 3 is a discussion of how we experience time to be slow or fast. Two possible explanations are the fraction of life: later in life a time interval is a smaller portion of your past and therefore experienced as being shorter, i.e., time runs faster. Another explanation is the 'new experience theory' which states that if our brain has to process more new experiences then time seems to pass slower, while it seems to pass faster when experiences are familiar. That explains why driving to a place you never went before seems to take longer than the way back. However it does not explain while sitting in the doctor's waiting room takes so long.



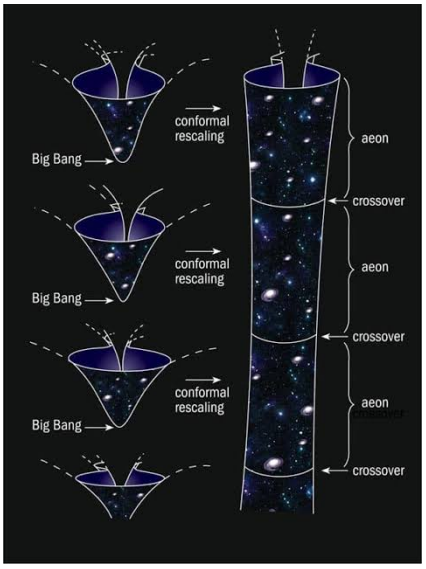
verge escapement

Chapter 4 is about if and how we can predict the future. Laplace viewed the world as a mechanical machine. Everything is predictable as long as we know the state of all the variables, the future can be computed by solving an initial value problem. But the current state can also be used as the state reached from the past. The math works in both time directions, which seems to contradict the arrow of time. Of course there is the chaotic behaviour as a consequence of the butterfly effect and since one electron at the boundary of the universe can influence (a system is never completely isolated) we should in fact know the state of everything in the whole universe if we want to predict accurately, That would rule out the existence of free will. But there are many other limitations like the Heisenberg uncertainty principle and whether or not information can be lost when it is absorbed by a black hole. The latter made Hawking and Penrose believe at some moment that the cosmos was not deterministic.

In the second part of the book, time is considered as a dimension. This is the place to explain the very strange time effects that follow from accepting that light is traveling at a constant speed in vacuum: the special and later the general relativity theory of Einstein is explained and all the time effects that these imply. Space and time become one 4D universe of spacetime, which leads to several paradoxes like the pole in the barn or the twin paradox if one is approaching the speed of light in special relativity or if one moves near a black home in general relativity. Here is mathematics with tensors and manifolds an essential tool but Khalili explains the effects elegantly avoiding the formulas. But still there is a discussion about the cosmic microwave background, that proves (if we accept the cosmological principle, i.e. that the universe is homogeneous and isotropic) the existence of a Big Bang, the expanding of a cosmos where space is infinite without boundary, Also the Friedmann-Lemaître equations derived from Einstein's field equations are discussed. These split spacetime again in space and time ($4 = 3 + 1$) in which space itself is flowing in time. There is a cosmological time which is the expansion of space = change = time.

Part three is about time as an arrow. This cannot be discussed without a definition and discussion of entropy, the beginning and the end of time, i.e. about the origin and ending of the cosmos. The entropy discussion is kept at a level of statistical mechanics. Khalili sees no problem in the fact that the symmetry and chaotic movement at low level will allow a directional effect at a larger scale. If a black hole increases its entropy, will it ever reach a maximum and fall back int an equilibrium, i.e., low entropy state? Such possibilities are also open for the whole cosmos: it may end in a Big Crunch (i.e. the expansion reaches a maximum, time is reversed and it shrinks back into a Big Bang situation), or will it end in a Big Freeze (it keeps

expanding and will end in a dark and cold void), or Big Rip (the cosmos keeps expanding at icreasing speed till it is teared apart) or a Big Bounce (it oscillates and shrinks after reaching a maximal expansion after which it starts expands again). A model of the latter type was propose by Thomas Gold (1960) in which time is reversed after a while, or there is Penrose's conformal cyclic cosmos where after a massive black hole has swallowed all mass, the Hawking leaking will recreate a situation of a new Big Bang at a new cosmic scale which can be repeated indefinitely. Why has there been a Big Bang and a beginning of time? Why were, at some point, all the physical constants just right to generate the universe that we live in? Thomas Hertog (Leuven) proposes that maybe all possibilities were present in quantum superposition, but because we are part of the system, our observations broke the superposition and generated the constants we know. We created our own universe as it is.



conformal cyclic cosmos (R. Penrose)

In a fourth part the reality of time is discussed. Here Khalili gets his final answers that he derives from quantum theory and quantum gravity for which some promising theories of Loop Quantum Gravity (LQG) and Causal Set Theory (CST) are explored. In CST, it is assumed that spacetime is fundamentally discrete, implying that no singulatities actually exist and that causality and A happening before B means that B is in the future light cone of A and this generates all physical measurements. The LQG theory also proposes a granularity of spacetime. It is related to the Wheeler-DeWitt equation which is a relativistic kind of Schödinger equation. However at this point it is still unclear if any of these theories is to be accepted. As mentioned above, the conclusion is that Khallili accepts time as being real and that the arrow of time comes from the irreversibility of quantum decoherence: once an observation is done, the quantum superposition disappears and cannot be undone.

I have mentioned many tings in this review, but many more are discussed by Khalili (Maxwell's demon, Boltzmann brain, Olbers and Loschmidt's paradoxes, etc.), and if all this sounds very complicated, if you read this book, it sounds all so simple and logical until you are surprised by some paradox that undermines what you believed to be correct so far. You are guided and showed around in a world that is very removed for your daily life and yet it is a world we are all part of.

I appreciated how Khalili really investigates all the possibilities and all the solutions that have been proposed, accepting or disposing them using reasonable arguments, never being dull or using high brow complicated expositions. He is really entertaining the reader.

As a bonus, Khalili provides a desert with a chapter about time travel. Will it ever be possible? What kind of paradoxes are awaiting us if we travel in time? Perhaps, it are not the laws of physics but the laws of logic that prevent time travel. The past can define the future but the future cannot influence the past. If there are two versions of yourself, this would add mass to the universe, and if you iterate we could create an impossible infinite mass. You cannot remember meeting your future self (bilking paradox) etc. It requires a multiverse to travel via wormholes in a block universe (where past and future coexist like space). Kurt Gödel wrote a paper in which he describes a time loop in a rotating universe. He obtained it by solving Einstein's field equations, so it was mathematically correct but physically impossible. It was not written because believed it, but he wanted to show Einstein (they were both in Princeton) that objective time did not really exist. Similarly other models have been computed compatible with Einstein's general relativity, but they were all very unrealistic. The most pressing question is: if ever time travel will be possible, then where are all these time travelers? They do exist, but so far only in literature and films and in our imagination.

Adhemar Bultheel