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The arrow of time

Paul Davies

Beyond Center for Fundamental Concepts in Science,
Arizona State University,
P.O. Box 871504, Tempe, AZ 852871504, USA.
Paul.Davies@asu.edu

Abstract

The arrow of time is often conflated with the popular but hopelessly muddled concept of the "flow" or "passage" of time. I argue that the latter is at best an illusion with its roots in neuroscience, at worst a meaningless concept. However, what is beyond dispute is that physical states of the universe evolve in time with an objective and readily-observable directionality. The ultimate origin of this asymmetry in time, which is most famously captured by the second law of thermodynamics and the irreversible rise of entropy, rests with cosmology and the state of the universe at its origin. I trace the various physical processes that contribute to the growth of entropy, and conclude that gravitation holds the key to providing a comprehensive explanation of the elusive arrow.

1. Time's arrow versus the flow of time

The subject of time's arrow is bedeviled by ambiguous or poor terminology and the conflation of concepts. Therefore I shall begin my essay by carefully defining terms. First an uncontentious statement: the states of the physical universe are observed to be distributed asymmetrically with respect to the time dimension (see, for example, Refs. [1, 2, 3, 4]). A simple example is provided by an earthquake: the ground shakes and buildings fall down. We would not expect to see the reverse sequence, in which shaking ground results in the assembly of a building from a heap of rubble. In daily life we are surrounded by such temporally-directed processes. It is merely necessary to play a movie of an everyday scene backwards —it immediately looks preposterous— to see how pervasive the directionality of physical processes in time is.

It is conventional to refer to the asymmetry of physical processes (sequences of states) in time by attaching an arrow to the sequence: "the arrow of time". Already there is a semantic trap lurking to confuse us. Note carefully that I have been referring to directed sequences of physical states in time, yet the common terminology is to assign an arrow *of* time (see, for example, Ref. [5]). This is seriously misleading. The arrow is a property of the sequence of physical states in time, not a property of time itself; it is a property of the world in relation to the time dimension. In this respect it is little different from the case of dimensions of space. Consider the spin of the Earth, which also defines an asymmetry between north and south. We sometimes denote that by an arrow too: a compass needle points north, and on a map it is conventional to show an arrow pointing north. We would never dream of saying, however, that Earth's north-south asymmetry (or arrow on a map) is an arrow of space. Space cares nothing for the spinning Earth. Similarly, time cares nothing for buildings falling down or rising up. Mathematically this is straightforward: perform a parity inversion of space and you would transpose Earth's north and south poles. Reverse the sign of time ($t \to -t$) and buildings would rise up. But these are heuristic tricks: we cannot physically reverse the parity of space or time.

There is now a second, more stubborn, misconception that I must deal with. This concerns the so-called flow or passage of time, about which much has been written by philosophers [6, 7, 8, 9]. In popular parlance one often describes time as flowing or passing. To add to the confusion, the arrow of time is sometimes identified with this flux or passage, with the arrow pointing in the "direction" that time is moving (i.e. towards the future). Note that this terminology conflates two arrow metaphors. One is the use of an arrow to indicate spatial orientation (as in a compass needle) and the other is the comparison with an arrow in flight, symbolizing directed motion.

The attribution of movement as a property of time is readily exposed as incoherent. Movement describes the change of state of something (e.g. the position of a ball) from one time t_1 to a later time t_2. Time itself cannot "move" unless there was a second time dimension relative to which its motion could be judged. The question, "how fast does time pass?" has only the trivial answer "one second per second" in effect, a tautology. To meaningfully ascribe a motion or rate of passage to time one would have to ask, how could you tell if that rate changed? What would be observably different about the world if time sped up or slowed down? Of course we can readily envisage human perceptions of events in time speeding up or slowing down, as when we watch action replays in sport, but this corresponds to a world in which the rate of brain/mental processes remains unchanged while the rate of everything else is changed.

There is no instrument that can measure the flow of time. Occasionally commentators will claim that a clock measures time's passage, but it doesn't. A clock measures intervals of time between events. It does this by correlating the position of the clock hand with a state of the world (e.g. the position of a ball, the mental state of an observer). Informal descriptions like "gravity slows time" and "time runs faster in space than on Earth" fuel the confusion. What these statements mean is that the hands of clocks in space rotate slower relative to the hands of identical clocks on Earth. One tests this by comparing clock spatial configurations. The most abusive terminology of all is talk about "time running backwards". Time doesn't "run" at all; the statement actually refers to the possible reversal in (unchanged) time of the normal directional sequence of physical states, e.g. rubble being assembled into buildings. It is not time itself, but the sequence of states, which "goes backwards."

All this has been pointed out by philosophers for over a century, but the river of time metaphor is so powerful that normal discourse is very hard without lapsing into it. Hard, but not impossible. Every statement about the world that makes reference to the passage of time can be replaced by a more cumbersome statement that makes no reference whatever to time's passage, but merely correlates states of the world at various moments to brain/mind states at those same moments. Consider for example the statement "With great anticipation we watched enthralled as the sun set over the ocean at 6 pm." Exactly the same observable facts can be conveyed by the ungainly statement: "The clock configuration 5:50 pm correlates with the sun above the horizon and the observers' brain/mental state being one of anticipation; the clock configuration 6:10 pm correlates with the sun being below the horizon and the observers' brain/mental state being one of enthrallment."

Nevertheless, it is undeniable that we possess a very strong psychological impression that our awareness is being swept along on an unstoppable current of time. It is perfectly legitimate to seek a scientific explanation for the feeling that time passes. The explanation of this familiar psychological flux is, in my view, to be found in neuroscience, not in physics. A rough analogy is with dizziness. Twirl around a few times and suddenly stop; you will be left with a strong impression that the world is rotating about you, even though it clearly isn't. The explanation can be traced to processes in the inner ear and brain. The feeling of continuing rotation is an illusion. In the same way, I submit, the sense of the motion of time is an illusion, presumably connected in some way to the manner in which memories are laid down in the brain.

Before I leave the topic of the (illusory) flux of time, let me deal with a final misconception which crops up a lot. The assertion that the flux of time is non-existent is often mistaken for the statement that time itself is non-existent. That is as silly as saying that if a ball is stationary, then space does not exist. Of course time exists. We measure intervals of time with clocks, just like we measure intervals of space with rulers. Furthermore, not only do intervals of time exist, moments of time can be ordered by inspecting sequences of physical states. There is a clear directionality to this order an arrow of time used in this case (correctly) in the sense that one can symbolically attach an arrow to a directed sequence of physical states such as buildings falling down. This property (of being able to attach an arrow) is a property of states of the world in relation to time. It is not a property of time.

Given that there is, then, a genuine property of the physical universe an arrow of time in the manner I have described it is natural to seek an explanation for its origin. So where does this arrow "come from"?

2. Entropy and the second law

The systematic study of the arrow of time began in earnest in the mid-nineteenth century with the development of thermodynamics and statistical mechanics. (A good introduction to the subject of thermodynamics can be found in Ref. [10]). A simple illustration of the arrow of time is to imagine an impenetrable rigid box divided by a barrier. On one side of the barrier is gas A, on the other side gas B. The barrier is then removed, and the two gases intermingle as their molecules, rushing around chaotically, collide randomly. After a time the two gases are homogeneously mixed. We would not expect the reverse sequence of events, in which two thoroughly mixed gases spontaneously separate themselves and retreat to opposite ends of a box. The mixing process thus provides a clear example of the arrow of time. A variant on the above experiment is if the gases were the same type but with different temperatures. When the barrier is removed, heat flows from the hotter gas to the cooler gas. The mechanism is well-understood: the molecules of the hotter gas on average move faster, so in collisions with the slower-moving molecules of the cooler gas, kinetic energy is transferred from the faster to the slower molecules. The process continues until a uniform temperature is attained throughout the gas, a state corresponding to thermodynamic equilibrium, in which there is no net energy exchange on average.

The foregoing irreversible activities of the gases can be described by defining a quantity called entropy, which (roughly speaking) is the measure of disorder in the gas. The initial conditions (unmixed gases or heat unevenly divided) clearly describe a more ordered state of the molecules than the final state of uniformity. The irreversible trend that follows the removal of the barrier may then be described as "a rise in the entropy of the gas." This sequence of events is captured by the so-called second law of thermodynamics, which affirms that, in a closed system (such as a box of gas), entropy cannot fall. For example, heat cannot flow spontaneously from a hot region of gas to a cold region of gas. (The word "spontaneously" here is important; a heat pump can transfer heat from cold to hot regions, as it does in a refrigerator, but only by doing work and expending energy, which itself drives up the entropy of the world by more than the transfer of the heat lowers it.) It follows that the state of thermodynamic equilibrium is one of maximum entropy.

Following its formulation in the mid-nineteenth century, the second law of thermodynamics soon found wide application not just in physics but in astronomy, chemistry, biology and engineering too. In fact, (almost) wherever an arrow of time is observed, the second law of thermodynamics is manifested. The one known exception refers to some processes in particle physics (such as the decay of the kaon) driven by the weak interaction, which display a slight difference in rate between the forward and backward directions. This small but important violation of time-reversal symmetry in particle physics does not have a direct bearing on the arguments I am presenting here. But where does the second law of thermodynamics come from? Physicists of the nineteenth century, notably Ludwig Boltzmann and James Clerk

Maxwell, set about deriving the second law of thermodynamics, at least in the simple case of a box of gas, by considering the mechanics of the gas's individual constituent molecules. Boltzmann studied what would happen to a collection of molecules confined to a rigid container, obeying Newton's laws of mechanics as they rushed around, colliding with each other and with the walls of the box. He was indeed able to prove mathematically by averaging the behavior of a large numbers of molecules that, if the gas was in a less-than-maximum entropy state, then the effects of the molecular collisions would be to bring about a subsequent rise in entropy.

This result was satisfactory and seemed to provide a sound basis for the second law. However, it soon became obvious that there was a problem. The laws of Newtonian mechanics to which Boltzmann appealed to describe the motion of the molecules are time reversal symmetric: they have no time direction built in. Thus any given molecular collision is reversible: run the molecules' trajectories backwards and they will go back to their starting configurations. In principle, if one could reverse all molecular motions simultaneously then two thoroughly mixed gases could spontaneously un-mix and retreat to opposite ends of a box. Furthermore, the French mathematical physicist Henri Poincaré was able to prove that, given long enough, precisely such an un-mixing process will happen [11]. In fact, under a wide range of circumstances, a closed box of gas containing molecules obeying Newtonian mechanics will re-visit (to within arbitrary closeness) any given physically permissible state, including any low-entropy starting state, and do so a limitless number of times. These so-called Poincar recurrences take, however, a stupendous amount of time. For a few grams of air trapped in a box, one would have to wait far longer than the age of the universe for the nitrogen and oxygen to un-mix and cluster at opposite ends of the box. Although these early formal analyses referred to simple molecules confined to a box, the broad conclusions carried over to all subsequent generalizations encompassing almost all physical phenomena. The second law of thermodynamics, inevitably arising from the statistical redistribution among many component parts from more to less ordered arrangements, is widely regarded as the most pervasive and most firmly-entrenched law of nature [10].

Although reversing trillions of molecules simultaneously is impracticable, and nobody can wait long enough to ever witness a familiar thermodynamic process running backwards, these nineteenth century mathematical analyses served to point up that the arrow of time is not intrinsic to the system itself (e.g. a box of gas), or to the laws that govern its evolution. Rather, the origin of the arrow of time resides in the initial conditions. If a system such as a box of gas starts out in a relatively well-ordered (low entropy) state, such as with the two gases spatially separated, then with high probability the system will subsequently evolve to a less ordered state. This principle of the trend from order to disorder describes all everyday experiences of the arrow of time (such as ordered buildings collapsing to disordered rubble).

A simple illustration involves a pack of cards. Imagine opening the box of a new pack, with the cards arranged neatly in suit and numerical order. If the cards are shuffled randomly then the pack is overwhelmingly likely to be less ordered afterwards. The arrow of time in this case clearly arises from the fact that the pack started out in a very special ordered state. The second law of thermodynamics is thus seen to be merely a statistical trend, not an absolute law. As a result, there is always a probability, albeit exceedingly small, that the law will be violated and the entropy will fall: there is a tiny, but non-zero, probability that random shuffling of cards will transform a jumbled sequence into suit and numerical order. Likewise, Poincar's recurrence theorem ensures that, sooner or later, the entropy of a gas is bound to go down, against the strictures of the second law of thermodynamics.

The principle of order giving way to disorder also describes the arrow of time on a grander scale. In our cosmic neighbourhood the most conspicuous example of the second law of thermodynamics is the flow of heat from the sun into the cold depths of space. The energy locked up in the sun in the form of hydrogen nuclei gets converted, via thermonuclear reactions, into photons. For each hydrogen nucleus fused, millions of photons flow from the solar surface into the far reaches of the universe never to return, a striking example of ordered energy (concentrated in a proton) being converted to less ordered energy (many photons scattered throughout space). The same general process is also happening across the universe as stars burn through their stock of nuclear fuel and eventually die, forming either white dwarfs, neutron starts or black holes. Thus the entire universe is on a one-way slide from order to disorder, from low entropy to high entropy. When this basic fact was realized in the mid nineteenth century, Hermann von Helmholtz and Lord Kelvin (William Thompson) referred to it as “the heat death of the universe” [12].

The fact that the entire cosmos seems to be doomed by the second law of thermodynamics, even though the time scales for decay and degeneration are vast, has exercised a profound effect on some philosophers and scientists. For example, Bertand Russell wrote in support of atheism [13],

> *[...] that all the labours of the ages, all the devotion, all the inspiration, all the noonday brightness of human genius, are destined to extinction in the vast death of the solar system, and that the whole temple of Man's achievement must inevitably be buried beneath the debris of a universe in ruins all these things, if not quite beyond dispute, are yet so nearly certain that no philosophy which rejects them can hope to stand [...] Only within the scaffolding of these truths, only on the firm foundation of unyielding despair, can the soul's habitation henceforth be safely built.*

3. The initial state of the universe

If the source of the arrow of time lies with initial conditions, then when applying the second law of thermodynamics to the universe as a whole we must consider the state of the universe at the time of its origin in a Big Bang. We expect that the state of the early universe should have had a lower value of its entropy than the present state. But at first sight there seems to be a paradox. Measurements, such as those performed by the European Space Agency's Planck satellite, indicate that the early universe was in a state close to maximum entropy, with matter and heat radiation spread smoothly through space in thermodynamic equilibrium at a common (very high) temperature. Indeed, the spectrum of the heat radiation left over from the Big Bang tracks the textbook form for radiation in thermodynamic equilibrium with matter (the so-called Planck spectrum) to an unprecedented level of accuracy. But if the universe began in equilibrium, why is it now in disequilibrium, when the second law of thermodynamics demands the opposite trend?

The answer lies with the nature of gravitation [2]. Let us return to the box of gas example. Imagine that the initial state consists of high-temperature hydrogen gas concentrated in a blob near the centre of the box. This low-entropy, ordered state soon disappears as the gas explodes outwards into the vacuum around it and fills the box at uniform density and maximum entropy. In accordance with the second law of thermodynamics we would not expect to encounter a box of gas uniformly filled in which the gas suddenly and spontaneously imploded to the middle. Now imagine that this set-up is scaled up to astronomical dimensions, so that the gravitational effects of the gas cannot be neglected. Our expectations are now very different. It would be no surprise to observe that a large distended cloud of gas shrinks towards the middle of the cloud. In fact, that is precisely our understanding of how stars form from giant molecular clouds distributed around the galaxy. Thus, whereas uniformity characterizes high-entropy states when gravitation is negligible, heterogeneity, or clumpiness, is the high-entropy state of gravitating systems. Viewed in this light the early universe, with its smooth distribution of matter and radiation, was a high entropy state of the matter and radiation degrees of freedom, but a low-entropy (close to minimum in fact) state of the gravitational degrees of freedom. As the universe expanded and cooled, the degree of clumpiness across the universe became amplified, elevating the gravitational entropy and complexifying the structure of the gravitational field, but at the same time driving the matter and radiation out of equilibrium. We now find ourselves in a typical cosmic location, living close to a concentrated gravitationally-bound ball of hot gas surrounded by cold empty space: the sun and its environs sits at a less-than-maximum matter/radiation entropy state as a trade-off for the less-than-minimum entropy of the solar system's gravitational configuration. (This trade-off is not, however, a zero sum game. Overall, the entropy has gone up.)

The sun's gravitational entropy is not, however, anywhere close to its maximum. Stars avoid further shrinkage under their gravitational self-attraction only by virtue of their internal heat, a situation sustained by the thermonuclear energy generation in their cores. When the fuel runs out the stars shrink, either slowly, or sometimes catastrophically. The ultimate end state of this process is a black hole, corresponding to a totally imploded object. If a black hole were totally black, i.e. possessing zero temperature, then its entropy would be infinite (one measure of entropy is heat energy divided by temperature). However, in 1975 Stephen Hawking, drawing on earlier work by Jacob Bekenstein, showed how quantum mechanics bestows a finite temperature on black holes, enabling a precise value to be assigned to the entropy of a black hole of given mass, electric charge and angular momentum [14, 15]. In the case of a solar mass black hole this entropy is about 10^{18} times greater than the entropy of the sun, which dramatically illustrates how far the sun's gravitational configuration is from its maximum entropy state.

Using the Bekenstein-Hawking formula for the entropy of a black hole, Roger Penrose estimated how far the gravitational state of the early universe is from the maximum value [16]. The current entropy is about 10^{100} k_B (where k_B, the units of entropy, is known as Boltzmann's constant). At the epoch (about four hundred thousand years after the Big Bang) to which the measurements of the Planck satellite pertain, the entropy was much lower about 10^{90} k_B. But the maximum possible entropy of the universe is about 10^{123} k_B. So the entropy at the current epoch, despite its enormous growth in the last 13 billion years, nevertheless remains exceedingly small (10^{-23}) relative to the maximum value [17].

4. The origin of the arrow

We are thus left with a straightforward explanation for the arrow of time. The universe started out in a low-entropy gravitational state and a high-entropy matter/radiation state. As the universe evolved, the entropy of the gravitational field rose, and in return a thermodynamic disequilibrium was established in the matter and radiation degrees of freedom. The latter disequilibrium, exemplified by the heat gradient around the sun, drives most of the familiar everyday entropy-generating, arrow-of-time-manifesting processes we observe on and near Earth. This process has a long way to run before the universe reaches the modern equivalent of the nineteenth century heat death (maximum entropy). But this simple summary glosses over many details, such as:

1. The ultimate fate of the universe is by no means certain. Current evidence favors a universe dominated by "dark energy" a type of vacuum energy that anti-gravitates, and so, unlike normal gravitational attraction that pulls matter into clumps, it pushes matter out towards less inhomogeneous states. Eventually the smoothing out may dominate the pulling in.

2. There is no general definition of the entropy of the gravitational field that incorporates black holes, dark energy and various states of matter, so the foregoing account in terms of gravitational entropy must be regarded as informal and non-rigorous.

3. The story of the universe from 400,000 years onward, which I have sketched, leaves out the complexities of the entropy story in the period from the moment of the Big Bang up to 400,000 years. This includes interactions with other players, such as neutrinos and supermassive particles that may have dominated the state of the universe before 10^{34} s. The "entropy story" of the universe during the first split second is a work in

progress, but certainly involved at least one epoch of non-equilibrium, during which the (small) asymmetry between matter and antimatter was established.

The main item of unfinished business is the origin of the gravitationally smooth, low-entropy state of the early universe. To explain the arrow of time I have appealed to very special cosmological initial conditions; how does one explain those initial conditions?

There is no agreed answer to the question of why, or how, the universe we know emerged from the Big Bang in a gravitationally low-entropy state. I shall mention just three possible answers. The first is to simply accept the initial conditions as a brute fact, in much the same way that most physicists accept the laws of physics as brute facts; they do not seek an explanation. The second answer is to appeal to a physical process known as inflation, which is the current standard account of the very early universe. According to the inflation theory, just after the Big Bang the universe leapt in size ("inflated") by a stupendous factor, driven by a huge pulse of "antigravity" or dark energy, as mentioned above, but overwhelmingly greater in strength, with the universe doubling in size in about 10^{34} s. During this inflationary phase, any prior irregularities in the distribution of matter and energy were "stretched to oblivion", ensuring that, when the universe exited this brief episode of frenetic and accelerating expansion, it was rendered exceedingly smooth, a bit like a crinkly balloon gets smoothed out as it is blown up. (For a popular account of the very early universe, see, for example, Ref. [18].)

Inflation goes some way to explaining the low-entropy state of the early universe but it shifts the question of the ultimate origin of the arrow of time back a step. Inflation is not an episode of magic, but a physical mechanism that itself requires certain initial conditions. (The details need not concern us.) So one may still ask why the universe began with the inflationary mechanism primed for action. A possible way around this issue involves extending the theory to what is known as eternal inflation [19]. In this picture a god's-eye-view would reveal inflation as having no beginning or end; it is the natural permanent state of cosmic affairs. What happens is that "bubbles" of expanding, but non-inflating, space pop out of this inflating superstructure randomly, each new bubble representing a Big Bang. Thus the Big Bang that initiated our universe is just one of an infinite number of big bangs scattered throughout ever-inflating space and time, each automatically smoothed by the preceding inflation. It is then but a small step to time-reversing this entire story and imagining an epoch in the arbitrarily far past in which the overall superstructure was contracting and universes were blinking out in tiny bubbles instead of appearing. Overall, there is time symmetry (as the symmetry of the underlying laws suggests), but any given bubble universe has an arrow of time pointing away from its small bubble phase, with those at late times pointing to what we call the future, those in the (very!) far past pointing toward what we call the past. Universes are thus guaranteed to possess an arrow of time (and to start small and grow bigger), but the direction of that arrow can be either way relative to other universes.

A different approach is to appeal to quantum cosmology, a subject created by John Wheeler and Bryce DeWitt [20], and further developed by James Hartle and Stephen Hawking [21]. In applying quantum mechanics to the universe as a whole, one assigns a wave function to represent the state of everything, including the gravitational field. In quantum mechanics the wave function generally consists of a superposition of an infinite number of branches, each branch representing a possible reality. Most quantum cosmologists accept the many-universes interpretation [22] according to which every branch possesses equal ontological status, and so represents a complete cosmic history in its own right. Quantum cosmology thus presents us with a description in which (generally infinitely) many universes co-exist and develop alternative histories in parallel reality. Applying this description to the arrow of time problem, it is simplest to restrict attention to universes that expand from a big bang, attain a maximum size, and then re-contract to a big crunch. In this picture, the wave function describing the entire ensemble of branches, or universe histories, evolves in a unitary manner. That is a technical way of saying that there is no preferred time direction, no change in entropy overall. However, within any particular branch the story is different. Some branches will represent universes that start out in a low-entropy state at the Big Bang and end up at a high entropy state at the big crunch (in the same branch), while others will do the reverse low entropy at the big crunch and high entropy at the Big Bang except that the arbitrary labels "bang" and "crunch" can readily be reversed to conform to the convention that the arrow of time should always point away from the low entropy end which one designates as the Big Bang. Any conscious beings, whose brain processes would be embedded in the general directionality of the entropy increase, would perceive "the past" to be the direction of the Big Bang. Yet overall, considering the entire assemblage of branches (universes) there is no preferred directionality. It is also curious to consider that some very rare branches would have low entropy at both ends (bang and crunch). In these universes the arrow of time would reverse at some stage. Occasionally it is claimed that our universe could be like this, but it seems likely that if it was we would notice [23].

The explanations for the origin of the arrow of time briefly described here are predicated on the standard model of cosmology, with all its hidden assumptions about the nature of space, time, gravitation, matter and immutable laws. It is entirely possible that this over-arching conceptual framework will one day be replaced by something radically different (e.g. time-dependent laws, spacetime as emergent), in which case the origin of the arrow of time would need to be sought in an entirely different manner [18].

5. Summary

States of the physical world evolve in time in a distinctive directional manner, familiar from everyday experience. The most embracing description of this directionality is provided by the second law of thermodynamics, which defines a quantity called entropy that (in a closed system) may go up, but not down, as a function of time. Entropy is very roughly a measure of disorder in a physical system. One may therefore attach an "arrow of time" to physical processes pointing in the direction of increasing entropy. The arrow describes a property of the world, namely the asymmetric evolution of states, in relation to time, not a property of time itself. Many commentators conflate the arrow of time with the popular notion of a flow, or passage, of time the psychological impression (many would say illusion) that time itself is moving. This notion is at best incoherent, at worst just plain wrong. (A dissenting view is taken by George Ellis: see paper in this volume.) In any case, there is no known instrument that can detect the flow of time. (Clocks measure time intervals between events, not the movement of time.) The position favoured by many is that the flow of time does not exist, but this conclusion must not be taken as a statement that time does not exist. Time does exist.

The time asymmetry of the world based on the second law of thermodynamics at first seems paradoxical, because the laws of physics (with a minor exception not relevant to this essay) are symmetric in time. The resolution of the paradox came with the understanding that the second law is statistical in nature and merely predicts with a very high probability, not certainty, that entropy will rise. The high probability comes about because of the special initial conditions that pertain to systems displaying an arrow of time. Roughly speaking, if a (closed) system starts out in an improbable, low-entropy, state then, with high probability, the entropy of the system will increase.

An interesting scientific question is the ultimate origin of the low-entropy initial state. As all systems examined by science form part of larger systems in a hierarchy terminating in the universe as a whole, it is natural that the origin of the arrow of time should be sought in the subject of cosmology. Physicists have known for 150 years that the universe is on a one-way slide from more ordered (low-entropy) states to less ordered (higher-entropy) states, perhaps culminating in a final "heat death" when thermodynamic equilibrium is attained. Thus an explanation for the arrow of time must focus on the origin of the universe and why the state of the universe that emerged from the Big Bang was one of low entropy. Here another apparent paradox emerges, because observations suggest that the early universe was actually in a state very close to thermodynamic equilibrium (maximum entropy). However, while this is true for matter and radiation, it is not true for the gravitational field. The highly ordered, near-uniform, distribution of matter and energy just after the Big Bang corresponds to a low-entropy state of the gravitational field. As the universe evolves by expansion and the gravitational aggregation of matter, a thermodynamic disequilibrium opens up in the matter/radiation component, but at the same time the gravitational field becomes less ordered, so its entropy rises. Overall, the total entropy increases with time, in accordance with the second law of thermodynamics. The end state of this gravitational clumping and disordering is a black hole, which has very high entropy.

There is no agreed explanation for why the universe was born in a near-uniform low-gravitational-entropy state, although a popular theory, called inflation, leads naturally to such a state after a very brief period of hyper-expansion. But inflation in turn requires special initial conditions, thus shifting the origin of the arrow of time back one step, so not providing an ultimate explanation. A tempting solution of this conundrum is to posit a more elaborate cosmological model, using quantum mechanics applied to the universe as a whole, in which there is not one universe but many (normally an infinite number), some of which have an arrow pointing this way, others pointing that way. Overall there is no favored directionality to the arrows, but within almost all universes the arrow points consistently only one way during its (possibly infinite) lifetime. Exceedingly rarely a universe may possess an arrow of time which then reverses. Given astronomical and physical observations, it is far from clear that our own universe could belong to this exceptional class.

Bibliography

1 Gold, T. (ed.) (1967). *The nature of time* (Cornell University Press: Ithaca).
2 Davies, P.C.W. (1974). *The physics of time asymmetry* (University of California Press: Berkeley).
3 Flood, R., and M. Lockwood (1991). *The nature of time* (Wiley-Blackwell: Oxford).
4 Lineweaver, C.H., P.C.W. Davies and M. Ruse (2013). *Complexity and the arrow of time* (Cambridge University Press: Cambridge).
5 Highfield, R. and P. Coveney (1992). *The arrow of time* (Ballantine Books: New York).
6 McTaggart, J.E. (1908). "The unreality of time", *Mind* 17 : 456.
7 Smart, J.J.C. (1949). "The river of time", *Mind* 58 : 483.
8 Williams, D.C. (1951). "The myth of [assage", *Journal of Philosophy* 48 : 457.
9 Grünbaum, A. (1963). *Philosophical problems of space and time* (Knopf: New York).
10 Atkins, P. (2007). *Four laws Ttat drive the universe* (Oxford University Press: Oxford).
11 Barreira, L. (2006). "Poincaré recurrence: old and new," in Zambrini, Jean-Claude, *XIVth International Congress on Mathematical Physics* (World Scientific: Singapore), p. 415.
12 Thompson, W. (1852). "On a universal tendency in nature to the dissipation of mechanical energy", Proceedings of the Royal Society of Edinburgh, April 19.
13 Russell, B. (1903). "The free man's eorship", reprinted in Volume 12 of *The Collected Papers of Bertrand Russell* (Routledge: London, 1985).
14 Bekenstein, J. D. (1973). "Black holes and entropy", *Physical Review D* 7 : 2333.
15 Hawking, S.W. (1975). "Particle creation by black holes", *Communications in Mathematical Physics* 43 : 199.
16 Penrose, R. (1979). "Singularities and time-asymmetry", in *General Relativity: An Einstein Centenary Survey*, eds. S.W. Hawking and W. Israel (Cambridge University Press: Cambridge), 581
17 Egan, C.A. and C.H. Lineweaver (2010). "A larger estimate of the entropy of the universe," *Astrophysical Journal* 710 : 1825.

18 Davies, P.C.W. (2007). *The Goldilocks Enigma: why is the universe just right for life?* (Allen Lane: London).
19 Linde, A.D. (1986). “Eternally existing self-reproducing chaotic inflationary universe”, *Physics Letters B* 175 : 395.
20 DeWitt, B. S. (1967). “Quantum Theory of Gravity. I. The canonical theory”, *Physical Review* 160 : 1113.
21 Hartle, J.B. and S.W. Hawking (1983). “Wave function of the universe”, *Physical Review D* 28 : 2960.
22 Everett, H. (1957). “Relative state formulation of quantum mechanics”, *Reviews of Modern Physics* 29 : 454.
23 Davies, P.C.W., and J. Twamley (1993). “Time symmetric cosmology and the opacity of the future light cone”, *Classical and Quantum Gravity* 10 : 931.

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