The Arrow of Time

Why do we remember the past and not the future? And what does the fact that time moves forward say about the universe?

In *The Curious Case of Benjamin Button*, Brad Pitt's character is born as an old man and grows younger as time passes. This is a clever narrative device, prodding us to think about the course of our lives in a different way. And there is a good reason why reversing the relative direction of time is an effective tool of the imagination: in the actual, nonimaginary world, it never happens. Time has a direction, an arrow pointing from the past to the future, and it has the *same* direction for everybody.

What does it mean to say that time has a direction? Think about watching a movie played in reverse. Generally, it's pretty clear if we are seeing something running the "wrong way" in time. A classic example is a diver and a pool. If the diver dives, and then there is a big splash, followed by waves bouncing around in the water, all is normal. But if we see a pool that starts with waves, which collect into a big splash, in the process lifting a diver up onto the board and becoming perfectly calm, we know something is up: the movie is being played backward.

Certain events in the real world always happen in the same order. It's dive, splash,

You can turn an egg into an omelet, but not an omelet into an egg. Ice cubes melt, but water doesn't spontaneously form ice cubes. These are examples of irreversible processes, which are at the heart of the arrow of time.

by Sean Carroll

waves, never waves, splash, spit out a diver. Take milk and mix it into a cup of black coffee; never take coffee with milk and separate the two liquids. Sequences of this sort are called *irreversible processes*. We are free to imagine that kind of sequence playing out in reverse, but if we actually see it happen, we suspect cinematic trickery rather than a faithful reproduction of reality.

Irreversible processes are at the heart of the arrow of time. Events happen in some sequences, and not in others. Furthermore, this ordering is perfectly consistent, as far as we know, throughout the observable universe. Someday we might find a planet in a distant solar system that contains intelligent life; but nobody suspects that we will find a planet on which the aliens regularly separate (the indigenous equivalents of) milk and coffee with a few casual swirls of a spoon. Why isn't that surprising? It's a big universe out there; things might very well happen in all sorts of sequences. But they don't. For certain kinds of processes—roughly speaking, complicated actions with lots of individual moving parts—there seems to be an allowed order that is somehow built into the very fabric of the world.

The arrow of time, then, is a brute fact about our universe, arguably *the* brute fact about our universe. The fact that things happen in one order and not in the reverse order is deeply ingrained in how we live in the world. Why is it like that?

The answer lies in the concept of *entropy*. Like energy or temperature, entropy tells us something about the particular state of a physical system; specifically, it measures how disorderly the system is. A collection of papers stacked neatly on top of one another has a low entropy; the same collection, scattered haphazardly on a desktop, has a high entropy. The entropy of a cup of coffee along with a separate teaspoon of milk is low, because there is a particular orderly segregation of the molecules into "milk" and "coffee," while the entropy of the two mixed together is comparatively large. All of the irreversible processes that reflect time's arrow—we can turn eggs into omelets but not omelets into eggs, perfume disperses through a room but never collects back into the bottle, ice cubes in water melt but glasses of warm water don't spontaneously form ice cubes—share a common feature: entropy *increases* throughout, as the system progresses from order to disorder. Whenever we disturb the universe, we tend to increase its entropy.

NATURE'S MOST RELIABLE LAW

The principle underlying irreversible processes is summed up in the second law of thermodynamics: the entropy of an isolated system either remains constant or increases with time. The second law is arguably the most dependable law in all of physics. If you were asked to predict what currently accepted principles of physics would still be considered inviolate a thousand years from now, the second law would be a good bet.

Our modern understanding of entropy was developed in 1877 by Ludwig Boltzmann, who was one of the few physicists at the time who believed in the existence of atoms. Boltzmann realized that when we look at some macroscopic system, we certainly don't keep track of the exact properties of every single atom. (If we have a glass of water in front of us, and someone sneaks in and, say, switches some of the water molecules around without changing the overall temperature and density and so on, we would never notice. There are many different arrangements of particular atoms that are *indistinguishable* from our macroscopic perspective.) And then Boltzmann noticed that low-entropy objects are more delicate with respect to such rearrangements. If you have an egg, and start exchanging bits of the yolk with bits of the egg white, pretty soon you will notice. The situations that we characterize as "low entropy" seem to be easily disturbed by rearranging the atoms within them, while "high-entropy" ones are more robust.

So Boltzmann took the concept of entropy, which had previously been defined as a measure of the uselessness of an object's energy content, and redefined it in terms of atoms: entropy is a measure of the number of particular microscopic arrangements of atoms that appear indistinguishable from a macroscopic perspective.

It would be difficult to overemphasize the importance of this insight. Before Boltzmann, entropy was a phenomenological thermodynamic concept, which followed its own rules (such as the second law). After Boltzmann, the behavior of entropy could be

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derived from deeper underlying principles. In particular, it suddenly makes perfect sense why entropy tends to increase in an isolated system: because there are more ways to be high entropy than to be low entropy.

At least, that formulation sounds like it makes perfect sense. In fact, it sneaks in a crucial assumption: that we start with a system that has a low entropy. If we start with a system that has a high entropy, we'll be in equilibrium—nothing will happen at all. That word *start* sneaks in an asymmetry in time, by privileging earlier times over later ones. And this line of reasoning takes us all the way back to the low entropy of the Big Bang. For whatever reason, of the many ways we could arrange the constituents of the universe, at early times they were in a very special, low-entropy configuration.

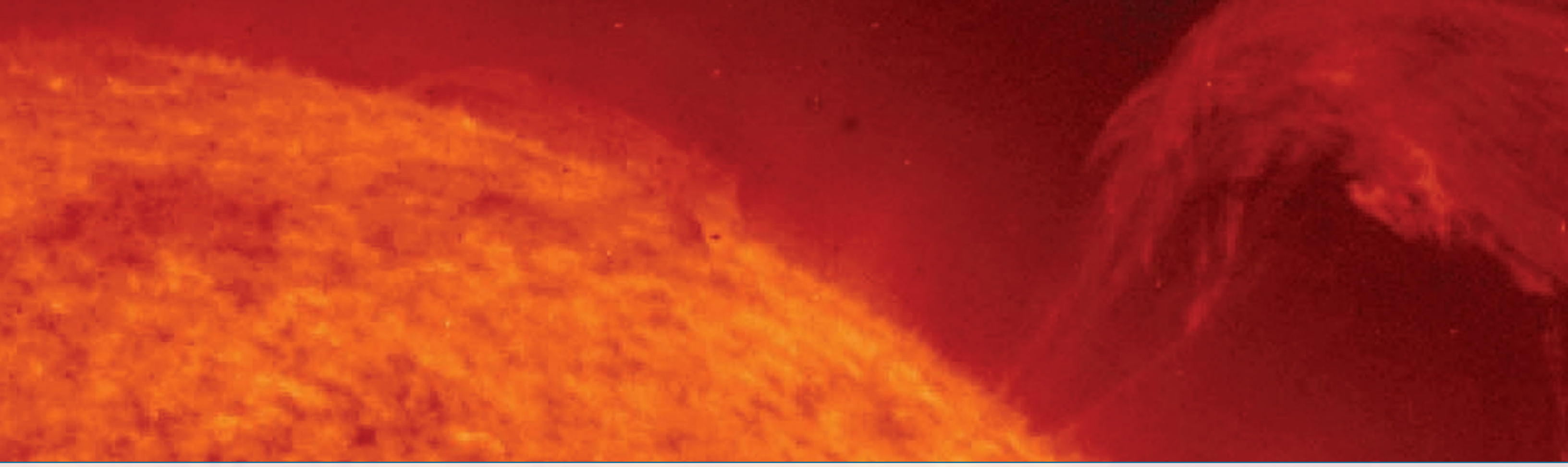
ENTROPY AND LIFE

This is all fascinating stuff, at least to physicists. But the ramifications of these ideas go far beyond steam engines and cups of coffee. The arrow of time manifests itself in many different ways—our bodies change as we get older, we remember the past but not the future, effects always follow causes. It turns out that *all* of these phenomena can be traced back to the second law. Entropy, quite literally, makes life possible.

The major source of energy for life on Earth is light from the sun. One consequence of the second law is that heat naturally flows from a hot object (the sun) to a cooler object (Earth). But if that were the end of the story, before too long the two objects would come into equilibrium with each other—they would attain the same temperature. In fact, that is just what would happen if the sun filled our entire sky, rather than describing a disk about one degree across. The result would be an unhappy world indeed. It would be completely inhospitable to the existence of life—not simply because the temperature was high, but because it would be *static*. Nothing would ever change in such a world.

In the real universe, the reason our planet doesn't heat up until it reaches the temperature of the sun is Earth loses heat by radiating it out into space. And the only reason it can do that is that space is much colder than Earth. It is because the sun is a hot spot in a mostly cold sky that Earth doesn't just heat up, but rather can absorb the sun's energy, process it, and radiate it into space. Along the way, of course, entropy increases; a fixed amount of energy in the form of solar radiation has a much lower entropy than the same amount of energy in the form of Earth's radiation into space.

This process, in turn, explains why Earth's biosphere is not a static place. We receive energy from the sun, but it doesn't just heat us up until we reach equilibrium; it's very low-entropy radiation, so we can make use of it and then release it as high-entropy radiation. All of which is only possible because the universe as a whole, and the solar system in particular, has a relatively low entropy at the present time (and an even



lower entropy in the past). If the universe were anywhere near thermal equilibrium, nothing would ever happen.

Nothing good lasts forever. Our universe is a lively place because there is plenty of room for entropy to increase before we hit equilibrium and everything grinds to a halt. It's not a foregone conclusion—entropy might be able to simply grow forever. But alternatively, entropy may reach a maximum value and stop. This scenario is known as the "heat death" of the universe, and was contemplated as long ago as the 1850s, amidst all the exciting theoretical developments in thermodynamics.

To this day, scientists haven't yet determined to anyone's satisfaction whether the universe will continue to evolve forever, or whether it will eventually settle into a placid state of equilibrium.

WHY CAN'T WE REMEMBER THE FUTURE?

So the arrow of time isn't just about simple mechanical processes; it's a necessary feature of the existence of life itself. But it's also responsible for a deep feature of what it means to be a conscious person: the fact that we remember the past, but not the future. According to the fundamental laws of physics, the past and future are treated on an equal footing; but when it comes to how we perceive the world, they couldn't be more different. We carry in our heads representations of the past, in the form of memories. Concerning the future, we can make predictions, but those predictions have nowhere near the reliability of our memories of the past.

Ultimately, the reason we can form a reliable memory of the past is that the entropy was lower then. In a complicated system like the universe, there are many ways for the underlying constituents to arrange themselves into the form of "you, with a certain memory of the past, plus the rest of the universe." If that's all you know—that you exist right now, with a memory of going to the beach that summer between sixth and seventh grades—you simply don't have enough information to reliably conclude that you really did go to the beach that summer. It turns out to be overwhelmingly more likely that your memory is just a random fluctuation, like the air in a room spontaneously congregating over on one side. To make sense of your memories, you need to assume as well that the universe was ordered in a certain way—that the entropy was lower in the past.

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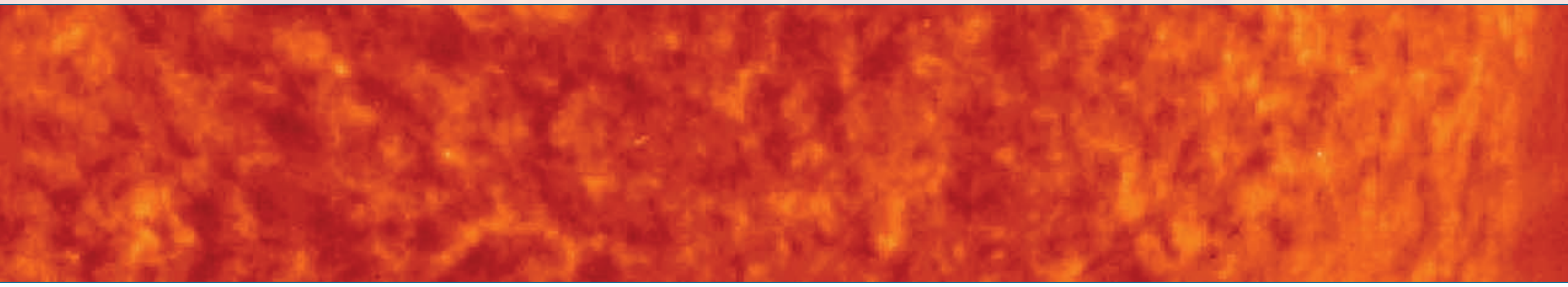
Imagine that you are walking down the street, and on the sidewalk you notice a broken egg that appears as though it hasn't been sitting outside for very long. Our presumption of a low-entropy past allows us to say with an extremely high degree of certainty that not long ago there must have been an unbroken egg, which someone dropped. Since, as far as the future is concerned, we have no reason to suspect that entropy will decrease, there's not much we can say about the future of the egg—too many possibilities are open. Maybe it will stay there and grow moldy, maybe someone will clean it up, maybe a dog will come by and eat it. (It's unlikely that it will spontaneously reassemble itself into an unbroken egg, but, strictly speaking, that's among the possibilities.) That egg on the sidewalk is like a memory in your brain—it's a record of a prior event, but only if we assume a low-entropy boundary condition in the past.

We also distinguish past from future through the relationship between cause and effect: namely, the causes come first (earlier in time), and then come the effects. Think of the diver splashing into the pool—the splash always comes after the dive. According to



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the microscopic laws of physics, however, it is possible to arrange all of the molecules in the water (and in the air around the pool, through which the sound of the splash travels) to precisely "unsplash" and eject the diver from the pool. To do this would require an unimaginably delicate choice of the position and velocity of every single one of those atoms—if you pick a random splashy configuration, there is almost no chance that the microscopic forces at work will correctly conspire to spit out the diver.

In other words, part of the distinction we draw between "effects" and "causes" is that "effects" generally involve an increase in entropy. If two billiard balls collide and go their separate ways, the entropy remains constant, and neither ball deserves to be singled out as the cause of the interaction. But if you hit the cue ball into a stationary collection of racked balls on the break (provoking a noticeable increase in entropy), you and I would say "the cue ball caused the break"—even though the laws of physics treat all of the balls perfectly equally.

THE ART OF THE POSSIBLE

Because we live in a universe with a pronounced arrow of time, we treat the past and future not just as different from a practical perspective, but as deeply and fundamentally different things. The past has already happened, while the future is still up for grabs in some sense—we can sketch out alternative possibilities, but we don't know which one is real. More particularly, when it comes to the past, we have recourse to memories and records of what happened. Our records may have varying degrees of reliability, but they fix the actuality of the past in a way that isn't available when we contemplate the future.

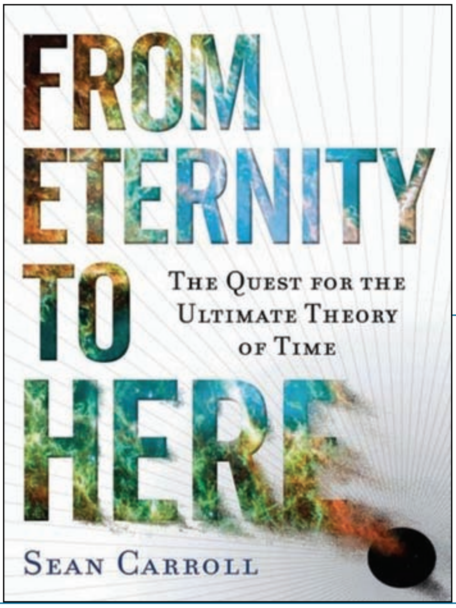
Think of it this way: A loved one says, "I think we should change our vacation plans for next year. Instead of going to Cancún, let's be adventurous and go to Rio." You may or may not go along with the plan, but the strategy, should you choose to implement it, isn't that hard to work out: you change plane reservations, book a new hotel, and so forth. But if your loved one says, "I think we should change our vacation plans for last year. Instead of having gone to Paris, let's have been adventurous and have gone to Istanbul," your strategy would be very different—you'd think about taking him or her to the doctor, not rearranging your past travel plans. The past is gone, it's in the books, there's no way we can set about changing it. So it makes perfect sense to us to treat the past and future on completely differently.

That distinction between the fixedness of the past and the malleability of the future is nowhere to be found in the known laws of physics. The deep-down microscopic rules of nature run equally well forward or backward in time from any given situation. If you know the exact state of the universe, and all of the laws of physics, the future as well as the past is rigidly determined beyond John Calvin's wildest dreams of predestination.

The way to reconcile these beliefs—the past is once-and-for-all fixed, while the future can be changed, but the fundamental laws of physics are reversible—ultimately comes down to entropy. If we knew the precise state of every particle in the universe, we could deduce the future as well as the past. But we don't; we know something about the universe's macroscopic characteristics, plus a few details here and there. With that information, we can predict certain broad-scale phenomena (the sun will rise tomorrow), but our knowledge is compatible with a wide spectrum of specific future occurrences. When it comes to the past, however, we have at our disposal our knowledge of the current macroscopic state of the universe, *plus* the fact that the early universe began in a low-entropy state. That one extra bit of information, known simply as the "past hypothesis," gives us enormous leverage when it comes to reconstructing the past from the present.

The punch line is that our notion of *free will*, the ability to change the future by making choices in a way that is not available to us as far as the past is concerned, is only possible because the past has a low entropy and the future has a high entropy. The future seems open to us, while the past seems closed, even though the laws of physics treat them on an equal footing.

The major lesson of this overview of entropy and the arrow of time should be clear: the existence of the arrow of time is both a profound feature of the physical universe, and a pervasive ingredient of our everyday lives. It's a bit embarrassing, frankly, that with all of the progress made by modern physics and cosmology, we still don't have a final answer for why the universe exhibits such a profound asymmetry in time. I'm embarrassed, at any rate; but every crisis is an opportunity, and by thinking about entropy we might learn something important about the universe.



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