The Arrow of Time

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1 Introduction

We know from everyday experience that time appears to permanently move in a single direction. We grow older and not younger, remember the past and not the future. If we accidentally drop a glass and it shatters, the glass doesn't somehow “unbreak”. We can't separate hot and cold water after mixing them to reach a lukewarm temperature, and watching a favorite movie backwards doesn't really make sense.

But although this phenomenon seems normal to us, it becomes more mysterious when considering the actual physics governing the particles that make up all of our world. It turns out that these laws of physics are time-symmetric: they don't have any preference for the past or future. Even if you completely reversed the equations, the laws themselves would work perfectly fine. So why, to us, does time seem to move in solely one direction when the fundamental equations have no preference?

This phenomenon is known as the “arrow of time”, a phrase usually attributed to Arthur Eddington in 1927.

2 Three Arrows of Time

In his book “A Brief History Of Time”, Stephen Hawking defines three distinct frameworks in which to view the passing of time.

- Thermodynamic Arrow of Time; time moves forward in the direction in which entropy increases
- Psychological Arrow of Time; the direction that humans perceive time processing (ex. the past occurs before the future)

- Cosmological Arrow of Time; time moves forward as the universe expands and backwards as the universe contracts

The most widely accepted explanation for the arrow of time problem comes from the Second Law of Thermodynamics. We will expand upon the Thermodynamic Arrow of Time as well as entropy and the Big Bang in the next sections before revisiting these three frameworks at a later point and considering possible connections between them.

3 Entropy and The Arrow of Time

The most widely accepted explanation for the arrow of time is related to the Second Law of Thermodynamics, which states that in a closed system, entropy tends to increase over time. Entropy is a measure of disorder. The more ways there are to arrange the parts of a system without changing its overall state, the higher the entropy of that system. This tends to increase naturally. For example, if you never clean your room, it will gradually become messier and more disorganized. Another example can be shown with a Rubik's cube– the number of ways the cube can be scrambled is much greater than the number of ways it can be perfectly ordered. Ludwig Boltzmann's main insight, building upon Rudolf Clausius's work, was that the Second Law of Thermodynamics is a *statistical principle* rather than a fundamental law. Nevertheless, as time goes on, systems tend to more probable (i.e. disorderly) states.

This creates a thermodynamic arrow of time: time moves forward in the direction in which entropy increases. Furthermore, this connection would explain things such as why a spilled glass of water doesn't jump back into the cup. Once the liquid has been spilled, the number of microscopic arrangements available is much greater than in the case where it was in the glass. Therefore, the original ordered state becomes extremely difficult to restore.

4 Time and the Big Bang

At the start of the 20th century, due to the findings of Edwin Hubble and others, it became known that space is expanding and galaxies are getting farther away from each other. It seems logical, then, that at an earlier time the universe was much smaller– so small that it began as a singularity (a single point) known as the Big Bang.

As the universe expands, entropy increases. Therefore, the universe began in a highly ordered initial state. But why did the universe start out in such an improbable, low-entropy state to begin with?

If the Second Law of Thermodynamics justifies the arrow of time, it requires this low-entropy state at the start. However, physics laws don't currently explain exactly why the universe began this way.

Roger Penrose claimed that the Big Bang must have been regulated not in terms of matter or energy density, but rather in terms of entropy. He put forth the *Weyl curvature hypothesis* in 1979, which states that the degrees of freedom for gravity were very low initially (i.e. spacetime was weirdly smooth). As the universe progressed, gravitational clumping (causing effects such as galaxies, stars, and black holes) increased entropy and therefore also induced an arrow of time.

(Why does gravitational clumping increase entropy? It may be a bit counter-intuitive at first because things clumping together seem to suggest more order. However, in terms of gravitational entropy, it actually causes more *disorder*. Compared to a uniform gas, when that gas collapses into stars and galaxies, there are many more configurations for the gravitational field.)

This means the structure and progression of the universe themselves are related to the arrow of time. The rise of complex formations may be a result of the way gravity and thermodynamics interact.

5 Three Arrows of Time, Revisited

Hawking asserted that the psychological arrow of time must point in the same direction as the thermodynamic arrow of time because the brain also follows the Second Law of Thermodynamics. Memory is a physical process (for instance, neurons are firing and molecules are shifting), and so is governed by thermodynamics. Our brain can retain information about past low-entropy states of the world. However, we can *only* remember past events because they form a small set compared to the vast number of attainable disordered future sets. The future contains a variety of possible configurations but the past can be thought of as a single, increasingly disordered thread that we are able to trace.

Scientists such as Sean Carroll also support this view, adding that our ideas of cause and effect are based on the directionality of thermodynamics. Events in the past influence events in the future since the mechanics of our universe favor states with greater entropy. Therefore, our psychological sense of time's directionality is rooted in the laws of physics.

Another potential arrow of time is the cosmological one. However, mere expansion is not enough to determine an arrow of time. General relativity allows for both expanding and contracting universes, which means that a contracting universe could still have increasing entropy given suitable conditions. Therefore, although the cosmological and thermodynamic arrows of time do frequently align, they are *not* necessarily the same. That being said, the expanding nature of this universe does play a role in creating conditions that allow for entropy to increase.

6 The Anthropic Principle

The anthropic principle, discussed by Hawking, states that the universe wasn't "designed" in some way specifically for "intelligent" life-forms to develop. Rather, we find ourselves in such a universe because otherwise we wouldn't exist.

For instance, if our world was 2-D (imagine a drawing of, say, a horse, on a piece of paper) creatures wouldn't be able to survive. To pass each other, animals would have to go on top of each other. The process of digestion wouldn't really work because if there was a connected set of openings, the animal would be split into pieces. Similarly, Hawking suggested that a thermodynamic arrow of time was necessary for existence. For example, we eat food (a more ordered form of energy) and convert it to heat (a more disordered form of energy), increasing entropy. If the universe had developed with different fundamental laws, we may not be in it.

The weak anthropic principle postulates that one observes the universe as having the correct conditions for existence simply because if it didn't, there wouldn't be anyone around to observe it. Hawking stated that while the weak anthropic principle is true, it doesn't explain *why* the universe formed the way it did.

You may be thinking that if there is a "weak" anthropic principle, there might be a "strong" version too. There is. The strong anthropic principle puts forth two possibilities: either there are an infinite amount of universes, each with their own set of physical laws, or our universe is infinitely-sized with different sets of physical laws in different regions of the universe such that the correct conditions for existence occur somewhere. Of course, human observers would only exist in regions that permit their existence.

7 The Quantum Arrow of Time

So far we have been concentrating on the macroscopic world, but what about the arrow of time at a microscopic level? Quantum theory is based on probabilities and wavefunctions governed by Schrödinger's equation. Let's consider decoherence. When a quantum system interacts with its environment, its wavefunction of numerous superposed states collapses into a single, classical, result. So far, this process seems to be permanent and irreversible– once decoherence occurs, the original superposition is gone. Therefore, this process seems to be time-asymmetric– just like the Second Law of Thermodynamics.

Not too much is known regarding a quantum arrow of time or how it relates (if it does indeed relate) to other arrows of time. Nevertheless, there are scientists with ideas about it and a few of those ideas will be examined below.

Some physicists claim that decoherence creates a quantum arrow of time. Each interaction increases entropy by entangling the quantum system with its environment and therefore aligns with the thermodynamic arrow of time. Others say that the act of observation, which requires memory and keeping a record of processes, bridges quantum events with the psychological and thermodynamic arrows of time.

Furthermore, hypotheses such as the Many Worlds theory state that the wavefunction never actually collapses. Instead, every outcome occurs in branching universes. In this idea, the arrow of time is related to the increasing complexity of the branching structure.

Yet other physicists (namely, Ahanorov, Bergmann, and Lebowitz in the 1960s), question the apparent time-asymmetry of quantum mechanics. From their experiments, they concluded that one only gets time-asymmetric answers in quantum theory when one asks time-asymmetric questions. Experiments can be framed in such a way that time-symmetric outcomes are possible.

8 Recent Findings

At the beginning of this year, a study by physicists at the University of Surrey provided evidence suggesting that, at the quantum level, time can actually emerge in two opposite directions. This challenges the idea that time always flows in one direction (forwards).

The study focused on open quantum systems (quantum systems that are able to interact with their environment). Usually, these interactions are described in terms of equations that include assumptions about the flow of time. Earlier experiments suggested that at the quantum level, there was also a singular arrow of time due to the breaking of time-reversal symmetry.

However, the physicists at the University of Surrey realized that when the Markov approximation (an approximation commonly used when dealing with quantum mechanical systems) is applied correctly, the quantum systems actually do not break time-reversal symmetry. This indicates that quantum systems can move towards equilibrium both forwards and backwards in time (basically, instead of just one arrow of time, there are two that point in opposite directions). Going back to entropy, this means that from the ”present”, we may observe two diverging arrows; one in which entropy increases into the future and another in which entropy increases into the past.

What are the consequences of such a discovery? For one, if two arrows of time exist in quantum systems, scientists may need to redefine time in the case of thermodynamics. The Second Law of Thermodynamics might not be an absolute rule but rather a result of an initial choice of time's direction. Another implication can be found when discussing the nature of time during the Big Bang. For instance, it could be possible that the Big Bang set off two opposing arrows of time— so another universe could exist that is the mirror image of ours and runs in the opposite time direction (from future to past).

9 Conclusion

One of the mysteries in physics is why time moves the way it does. Recent research suggests that time having a specific direction may not be a fundamental property of the universe but rather a property that occurs under specific conditions.

Some further questions that have been posed about this topic include: how do the two opposing arrows of time interact with each other in more complicated quantum systems? Could such experiments help unify the theories of quantum mechanics and general relativity into a hypothesized Grand Unified Theory? And is time itself necessarily a fundamental property of reality or simply one that emerges under certain conditions?

Studying the nature of time also brings in philosophical questions such as: is time actually a real dimension like space, or is it a construct of our minds? Do the past and future really exist, or is only the present real? Is the arrow of time simply an illusion due to entropy, or is it actually a fundamental feature of our universe? Can time ever change direction?

In any case, the nature of time seems to be even more complex than was previously imagined. We may only ever experience time going in one direction, but each new discovery leads us towards a bigger picture. And, by exploring the nature of time, we will gain more insight into the nature of existence itself– from the formation of galaxies to the inner workings of the human brain.

10 Sources Used

In this section, I have provided links to the articles I found relating to the arrow of time problem, and that I read while writing this paper.

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