BCA Research

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Global Investment Strategy

Special Report

December 21, 2021

Life, Death, And Finance In The Cosmic Multiverse

In this Issue

Dear Client,

Our reports usually consist of discussions of the global economy and financial markets. Occasionally, however, we like to look far outside the box, as we did a few years ago when we discussed how the recent decline in human intelligence threatens to undermine global productivity growth (see: The Most Important Trend In The World Has Reversed And Nobody Knows Why).

This week, we present you with another controversial report. I will be frank: This piece is not for everyone, which is why we are sending it so late in the year as a bonus to your existing subscription. But for those willing to go down the rabbit hole with me, what you will find is a wide-ranging discussion of how modern cosmology can be used to better understand not just financial markets but the nature of reality.

And with that, I will sign off for the year. I wish you and your loved ones a very happy and healthy 2022. We will be back in the first week of January with our next report.

Best regards,
Peter Berezin, Global Chief Strategist

P.S., If you haven't already, please check out our 2022 Key Views report published on December 2nd, as well as our webcast where I summarize the report and take questions from the audience. In addition, we published a Special Report from our Global Asset Allocation service on December 13th, which recommends reading materials on key themes of the moment, such as climate change, cryptocurrencies, supply-chain disruptions, and gene technology. Included in this report are my team's recommendations on what to read to understand the underlying causes of inflation.

Highlights

- The idea of parallel worlds seems like the stuff of science fiction. Yet, most leading cosmological theories suggest that the universe is vast enough to contain multiple copies of everything, including multiple copies of you.
- The existence of the "multiverse" may account for why the parameters of physics seem highly fine-tuned to support life and why the earth has escaped so many existential threats – major asteroid strikes, World War III, a more deadly strain of Covid, etc. The resulting survival bias helps explain why stocks have historically performed so well.
- Randomness is an illusion. Everything that could possibly happen to the stock market over the next 12 months will happen. As an investor, the best you can do is estimate the relative frequencies of various outcomes, as given by the Born Rule for quantum mechanics.
- Subjectively, you will feel immortal. When life-threatening events occur, it will always seem as though you miraculously pull through. This has major implications for financial decisions, not to mention how you live your life and see the world.

I. The Fine-Tuning Problem

The Goldilocks Universe

Our universe appears remarkably fine-tuned for life. If the relative masses of the elementary particles or the strengths of any of the four fundamental forces were slightly different, the universe would never have been able to create stars or galaxies – or us.

Consider the fine structure constant, which underpins the strength of the electromagnetic force. Richard Feynman famously called it "a magic number that comes to us with no understanding." It is roughly equal to 1/137. There is no particular reason why it has to be this value, other than chemistry as we know it would not exist if its value were any different.

Perhaps the most fine-tuned of all the parameters of nature is the density of dark energy, the mysterious force that is causing the universe to expand at an accelerating rate. Its value is tiny. However, because it suffuses all of space, it accounts for 70% of the mass of the universe. If the density of dark energy were slightly larger, the universe would have expanded so quickly after the Big Bang that matter would not have had the chance to coalesce into stars; if its value were slightly smaller, the universe would have quickly recollapsed onto itself.

Physicist Lee Smolin has estimated that there is just a 1 in 10^{229} chance that life could have randomly emerged in a universe where the constants of nature were chosen at random.

Explanations for Fine-Tuning

One possible explanation for why the parameters of nature appear so fine-tuned is that the laws of physics would break down if their values were any different. Even if this explanation were correct – and the evidence strongly suggests that it is not – it would not resolve the fine-tuning question. We would just have another question: Why did the laws of physics just happen to be so friendly for life?

Two alternative explanations present themselves. The first is that the universe is fine-tuned because there is a fine-tuner: God. The second explanation is that there are many universes comprising a multiverse.

According to the latter explanation, just as we should not be surprised to find ourselves living on a rocky planet with liquid water rather than on the surface of a star or in interstellar space, we should not be surprised to find ourselves living in the part of the multiverse where the parameters of nature permit life to flourish.

Before the Big Bang

There is something lacking from the Big Bang Theory. The Theory offers an incredibly accurate description of what happened in the moments after the Big Bang. It predicts, for example, that twenty minutes after the Big Bang, the universe should have consisted of 76% hydrogen, 24% helium, with traces of deuterium and lithium. The empirical data back this up.

It also predicts that roughly 400,000 years after the Big Bang, the universe went from being completely opaque – filled with a hot, dense plasma – to transparent. We can see this "first light" today in the form of the cosmic microwave background radiation.

Yet, as physicist Alan Guth has noted, the Big Bang Theory is silent on "what banged, why it banged, or what happened before it banged." To remedy this problem, Guth and his collaborators developed the Theory of Cosmic Inflation.

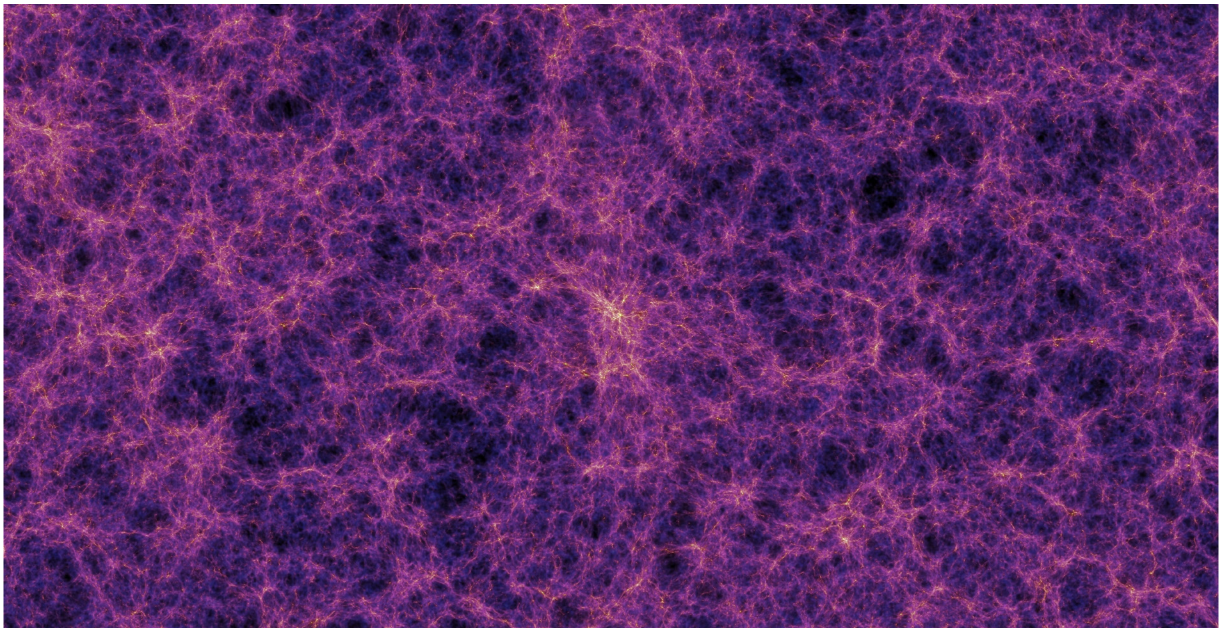
Einstein's equations for General Relativity permit gravity to be either attractive or repulsive. The mass of an object is always positive. Hence, mass always attracts. However, mass is not the only source of gravity. Pressure can also produce gravity. Positive pressure, of the sort generated by the air in your car's tire, produces the familiar attractive form of gravity. In contrast, negative pressure, such as the pressure generated by a stretched elastic band, produces repulsive gravity.

Bubble Universes

Guth's theory posits that the early universe was awash in repulsive energy, embedded in something called the "inflaton field." The presence of this field caused space to expand at an exponential rate.

The field, however, was unstable. Quantum fluctuations caused a portion of the field to decay, leading to the creation of a "bubble universe." As the bubble expanded,

FIGURE 1
The Large-Scale Structure of the Universe



SOURCE: VOLKER SPRINGEL (MAX PLANCK INSTITUTE FOR ASTROPHYSICS) ET AL. VIA ESA/HUBBLE.

tiny quantum fluctuations got stretched out across space, resulting in slightly more particles being created in some parts of the universe than in others. Over time, these particles agglomerated into a patchwork of galaxies and galaxy clusters, all strung out in beautiful filaments (**Figure 1**).

While the process underlying cosmic inflation sounds very exotic, something analogous happens in everyday life. Liquid water normally boils when its temperature rises above 100° Celsius and freezes when the temperature falls below 0°. However, if the water is in a highly purified form, it can remain liquid outside of this temperature range, wherein it becomes metastable – it can decay into a different state if given a slight jolt.

In the case of "supercooled" water, even a fairly small disturbance will cause a chain reaction in which water molecules are turned into ice crystals. Likewise, if you perturb a "superheated" cup of water, it will boil almost instantly. The bubble universes created during inflation were similar to the bubbles created in a cup of superheated water.

String Theory and Eternal Inflation

As Andrei Linde, Alex Vilenkin, and Paul Steinhardt have shown, inflationary theory strongly implies that once inflation starts, it never ends. The inflaton field just keeps creating more space in which new bubble universes can emerge. Every second, the number of bubble universes grows by many orders of magnitude – 1037 by some calculations – and this exponential process goes on forever.

The physical features of one bubble universe will tend to differ from the next. String Theory suggests that our universe contains nine spacial dimensions. We only see three dimensions (up and down, left and right, back and forth) because the other six are curled up, much like a rug appears to have only two spacial dimensions until one examines it at close range; or how a clothesline appears to be one-dimensional from afar but two-dimensional for a ladybug sitting on it.

According to String Theory, there are more than 10^{500} different ways in which these additional dimensions can be "compactified." Each compactification has the potential to produce its own universe with its own set of elementary particles and parameters of nature.

The Cosmic Landscape

Biologists often talk about the "landscape" of possibilities. By this, they mean all the different ways that DNA molecules can combine to form life. As Leonard Susskind points out, the analogue in physics is String Theory. String Theory describes a cosmic landscape of all the ways a universe can be configured.

Having a landscape of possibilities is not enough, however. One also needs a mechanism by which those possibilities can come into being. In biology, that mechanism is natural selection. In cosmology, the mechanism is Eternal Inflation.

We thus have a solution to the fine-tuning problem: The multiverse is incredibly big, so big that it contains myriad bubble universes with their own local physical properties. Most of these bubble universes are inhospitable to life. But if you look long enough, you will find some that are just right to support life. Naturally, we are living in one of those rare goldilocks bubble universes.

Summary: Our universe appears to be fine-tuned for life. The combination of Eternal Inflation and String Theory provides an explanation for fine-tuning. Inflation creates myriad bubble universes. String Theory suggests that these universes can take on a wide variety of physical properties. While most of the bubble universes in the cosmos are unsuitable for life, a few, by sheer chance, will possess all the properties necessary to produce life. It is not surprising that we find ourselves living in one of these "goldilocks" universes.

II. An Infinite Universe Within a Finite Space

Insiders Versus Outsiders

The term “bubble universe” seems to imply that every new universe produced by inflation is finite in size. The reality is more nuanced. The simplest version of inflation predicts that bubble universes are finite in size when viewed from the outside, but infinite in size when viewed from the perspective of someone living within that universe.

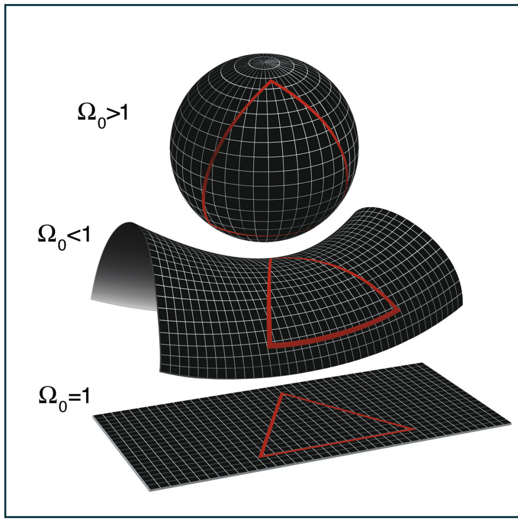
How can that be? The answer is that Einstein’s Theory of General Relativity allows space and time to be interchangeable in a very precise mathematical way. What one observer perceives as space, another observer can perceive as time, and *vice versa*.

When we observe the universe from within, we see it bounded by time. Since light takes time to reach us, the farther away we look, the further back in time we see. If we try to look too far into the past, we run into the cosmic background radiation, the ubiquitous afterglow of the Big Bang. Thus, all we can see is the region of space from which light has had time to reach us in the 13.8 billion years since our universe popped into existence.

An outsider would see things differently. Rather than seeing the universe as bounded by time, they would see it bounded by space, growing ever larger into the infinite future.

This brings me to a key point that I want to underscore because it is central to the ideas expressed in the rest of the report: One can view our universe from the inside, as one of its inhabitants, or one can view it from the outside, as an external observer. Both are valid perspectives, but sometimes the “outsider perspective” can shed light on the nature of reality in a way that the “insider perspective” misses.

FIGURE 2
Space Can Be Positively-Curved, Negatively-Curved, or Flat



NOTE: THE OMEGA SIGN IN THE ABOVE IMAGE REPRESENTS THE DENSITY OF THE UNIVERSE, WHICH ALSO DETERMINES ITS GEOMETRY. IF 1 IS THE CRITICAL DENSITY OF THE UNIVERSE, THE IMAGE ABOVE SHOWS THE DIFFERENT LEVELS OF CURVATURES IT WILL HAVE DEPENDING ON WHETHER ITS DENSITY IS ABOVE, AT, OR BELOW ITS CRITICAL LEVEL.
SOURCE: NASA/WMAP SCIENCE TEAM

Escher in the Sky

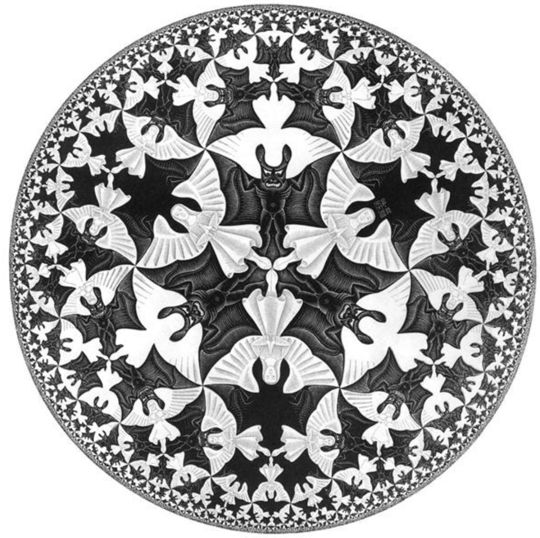
What is the shape of the universe? In principle, space can be positively-curved, negatively-curved, or flat (**Figure 2**). A sphere is a positively-curved object. The angles of a triangle drawn on a sphere will sum up to more than 180 degrees. Two parallel lines on a sphere will eventually converge, just like two lines of longitude on the earth will meet up at the north and south poles.

If you try to create a map of the earth's surface, you will find that you need to stretch everything out as you move further away from the equator. This is why Greenland looks just as big as Africa on a typical map, even though the former has only one-tenth the land mass of the latter.

In contrast to positively-curved surfaces, two parallel lines on a negative-curved surface, such as a saddle or a Pringles chip, will always diverge. The angles of a triangle on such a surface will sum up to less than 180 degrees. If you try to create a map of a negatively-curved surface, you will need to draw it so that the same objects get smaller and smaller the further from the center you go.

According to most inflationary models, bubble universes are negatively-curved on extremely large scales. If you have trouble imagining a negatively-curved universe, do not worry. The great artist M.C. Escher has already envisioned it. His woodcut *Limit Circle IV* depicts an infinite procession of angels and demons in what can be viewed as negatively-curve space (**Figure 3**). You can think of each angel and demon as a separate galaxy. No matter how far you travel, you will never reach the last galaxy. An infinite universe within a finite space.

FIGURE 3
Escher's Circle Limit IV



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How Far Is Your Nearest Twin?

Isaac Newton thought that the universe was infinite in size. Yet, if you had asked him how far he would need to travel before he met an exact copy of himself, he probably would have said infinitely far.

According to classical Newtonian physics, space can be arranged in an infinite number of ways. Think about the distance between any two objects in your room. Even if you could express this distance using a trillion decimal places, it still would only provide an approximate number. Specifying the *exact* number would require an infinite sequence of decimal places.

The world is not classical, however. It is quantum mechanical. As the word quanta implies, everything in our universe comes in discrete packets. This includes space and time, which cannot be expressed in anything less than one Planck unit.

Just as there is a finite number of ways to arrange a deck of cards, there is finite number of ways to organize everything in a given region of space. Once you have exhausted all the possible ways to reconfigure that space, you have to start repeating yourself.

The observable universe can be configured in about googolplex ($10^{10^{100}}$) different ways.[1] That is 1 with a googol zeros behind it.

I don't suggest you try writing out this number in full. Even if you could write ten sexvigintillion zeros (or 10^{82} zeros) every second, it would take you twice the current age of the universe to write a googol zeros (and remember, every time you add a single zero, you expand the volume of space by a thousand-fold).

Nevertheless, as big as a googolplex is, it is still a finite number.

If you could travel far enough in space, before you met your nearest twin, you would meet many people who were sort of but not exactly like your twin. For example, your near-perfect doppelganger may have had the exact same life experiences as you except that he or she grew up on a different street. For every true ringer for you, there would be countless others who were almost like you, and countless more who were different from you in more meaningful ways.

Summary: Inflation creates bubble universes that appear finite in space when viewed from the outside but infinite in space from the perspective of someone within the universe. There are a finite number of ways that the particles in any region of space can be arranged. Thus, if you can travel far enough, you will eventually encounter a region of space that is identical to your own. Your nearest identical twin probably lives about a googolplex meters from you.

III. The Illusion of Time

Personal Time

Of all the revelations of modern physics, the idea that time is much more than a passive stage on which events play out has to be one of the most mind-blowing. If you take two watches and lift one while lowering the other, the clock in your lower hand will tick slightly slower than the one in your raised hand. This is because gravity slows the flow of time, as memorably depicted in the scenes around the black hole Gargantua in Interstellar.

Likewise, if you were to put the first watch on your kitchen counter and walk to the end of the room and back with the second watch, the first watch would show more elapsed time than the second watch. Changes in velocity slow the flow of time too.

Imagine that you are standing in the middle of a carriage on a high-speed train, and you flip a switch to illuminate two bulbs, one at the front of the carriage and one at the back. From your perspective, both bulbs

[1] The holographic principle tells us that the maximum amount of information a region of space can contain is proportionate to its surface area. The surface area of our observable universe is about $10^{10^{122}}$ Planck units. That is the maximum number of ways (or "degrees of freedom") in which our observable universe can be arranged. A universe such as ours, which is only sparsely filled with matter, could get by with about $10^{10^{100}}$ degrees of freedom.

light up at the same time. From the perspective of someone watching the train from a platform as you whiz by, the bulb at the back of the carriage will light up first.

Disagreements over what constitutes "now" get bigger the farther apart two observers are. Suppose you and a friendly alien in a galaxy 10 billion light years away are initially at rest relative to one another. You would both agree that it is 2021 on earth. If your alien friend were to hop on his bicycle and pedal directly away from you, he could now claim that it was 1790 and George Washington was the president of the United States. If he were to pedal towards you, he could claim that it was the year 2250 on earth.

All of these examples highlight the fact that time is personal. If two observers are situated close to one another, and are not moving too fast relative to one another, they will both broadly agree on what is taking place "now." However, if they are far apart or moving fast relative to one another, they will end up disagreeing on what constitutes simultaneous events.

The Block Universe

Two years after Einstein published his Special Theory of Relativity, Hermann Minkowski, who had been Einstein's teacher and once described his young pupil as a "lazy dog," showed that Einstein's description of the universe could be regarded geometrically as a four-dimensional mathematical structure with three directions for space and one direction of time (**Figure 4**). Einstein initially brushed off Minkowski's reformulation of his work, only to later realize that his old teacher's insights were indispensable for developing his own theory of gravity, General Relativity.

This mathematical structure that Minkowski described would go on to be called Minkowski spacetime. Informally, it is known as the block universe.

Every object in the block universe has a world line, which traces a path through spacetime. Your world line starts with your birth and ends with your death. Everything that happens to you is indelibly imprinted into the fabric of the cosmos. Your first baby steps? As you read this sentence, they are being played out in the block universe, over and over again. The same goes with whatever you are about to do two hours from now.

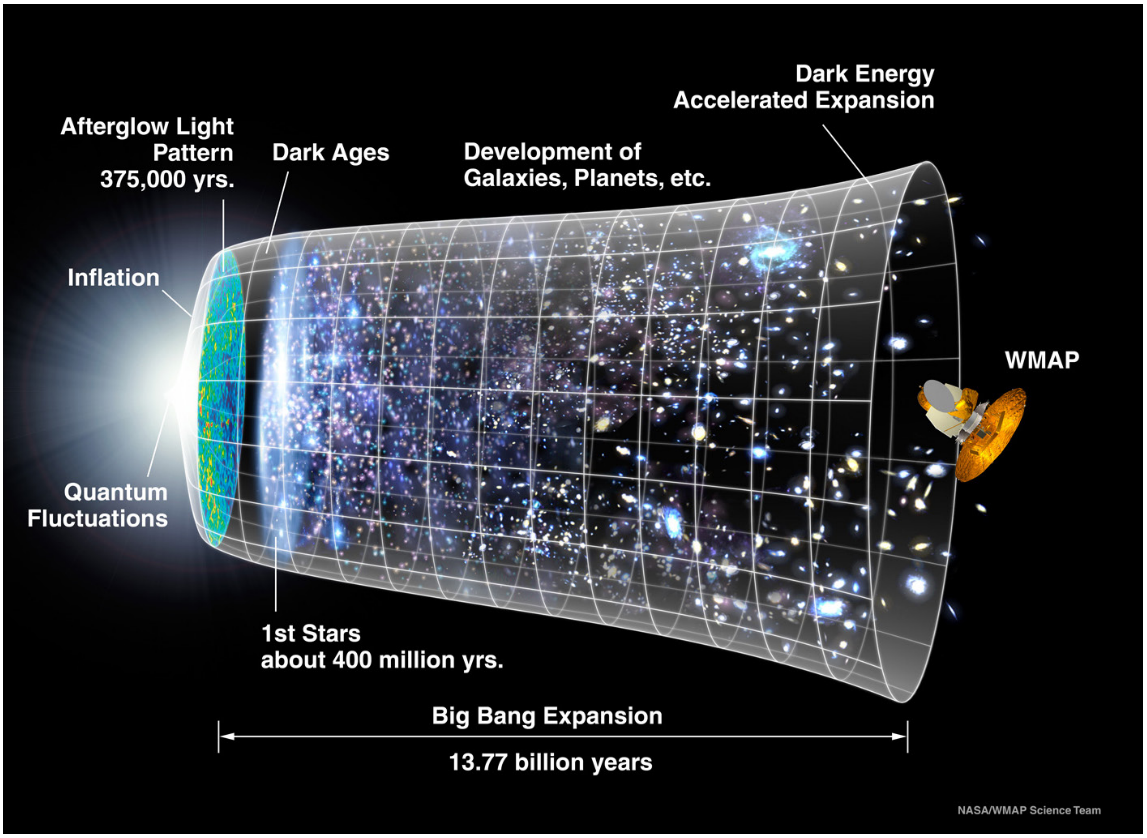
Free Will

Think of the universe as a DVD movie. From the perspective of the characters in the movie, time seems to flow. From your perspective, as a viewer, everything that happens in the movie is encoded in the DVD itself. The universe "just is." There is no flow of time.

Popular conceptions of free will are difficult to square with the block universe. "I know that philosophically a murderer is not responsible for his crimes," Einstein once said, before adding "but I prefer not to take tea with him."

Personally, I think the best way to reconcile free will with the block universe is to regard one's actions as *revealing* the future rather than determining it.

FIGURE 4
The Block Universe



Summary: What I regard as "now" and you regard as "now" can differ depending on how far away I am from you and how fast we are traveling relative to one another. Everything that happened to you in the past, and everything that will happen to you in the future, exists in perpetuity within the block universe. Your actions reveal your future rather than determining it.

IV. Why You Can Remember the Past but Not the Future

Entropy and the Thermodynamic Arrow of Time

The laws of physics are time reversible, meaning that they do not point to a special direction of time. For example, a film of the moon orbiting the earth looks the same whether you play it forward or backward.[2] The same is true for two billiard balls colliding, or someone throwing a ball up and down.

The one seeming exception to time reversibility is the second law of thermodynamics. The second law is not a law in the same way that, say, Newton's "force equals mass times acceleration" is a law. Newton's laws of motion are always true. In contrast, the second law is only statistically true. It states that there is an overwhelming tendency for any physical system to degenerate into a more random, less ordered state. Physicists have a name for such disorder: Entropy. The second law says that entropy almost always increases over time.

In physics, energy is always conserved. However, the form that energy takes can change. In Greek mythology, Sisyphus was condemned to roll a boulder up a hill, never able to reach the summit.[3] As he rolls the boulder towards the summit for the umpteenth time, the chemical energy that he acquired from his breakfast is converted into potential energy. As the boulder rolls back down the hill, its potential energy is converted into kinetic energy. The boulder's kinetic energy, in turn, is converted into thermal energy as it bounces down the hill, heating itself and the environment around it.

What is the difference between chemical energy and thermal energy? One key difference is that the former is a lot more structured than the latter. Carbohydrates, which are found in many food sources, contain a reservoir of chemical energy. They consist of highly structured molecules consisting of carbon, oxygen, and hydrogen. Thermal energy, in contrast, is generated from the random jostling of atoms and molecules. It is the physics equivalent to a mosh pit.

A video of poor 'ol Sisyphus played in reverse – where the boulder rolls up the hill by itself, followed by the cursed man walking backwards down the hill with his hands on the boulder – would look strange because such a sequence of events requires that highly disordered energy be converted into highly ordered energy. This is something that the second law of thermodynamics says is extremely unlikely to occur.

Entropy and the Big Bang

If entropy tends to increase over time, the universe must have been in an extremely orderly state shortly after the Big Bang. This may sound odd, considering one usually thinks of the early universe as an extremely hot, dense, and chaotic place. However, the early universe was incredibly homogenous.

2 You might argue that the moon does orbit the earth in a certain direction. However, that direction is simply a reflection of how you are oriented on earth. If you don't believe this, raise your hand above your head and then rotate your fist clockwise while you slowly lower your hand. You will notice that the rotation goes from clockwise to counter-clockwise as your hand falls below eye level.

3 I have borrowed this example from Leonard Susskind's fantastic book, The Cosmic Landscape.

Matter was almost perfectly spread out. This homogeneity put it into a very low entropy state.

Imagine a huge billiard table where each ball is placed along a grid. Compared to a haphazard arrangement where each ball is placed randomly on the table, the number of ways to arrange balls on a grid is very small.

If the universe had not been so homogeneous, matter would have coalesced into huge black holes very quickly. There would not have been enough time for life to form. We owe our existence to the fact that the entropy of the early universe was incredibly low.

Information and Entropy

Just as energy must be conserved within a closed system, the same is true for information. In principle, if you throw a book into a fire, you could recover its entire contents as long as you kept track of what happened to every particle in the book. In practice, doing so would be extremely difficult because, as with energy, information tends to become more random over time.

There are many more ways an egg can be broken than unbroken. Thus, when we compare a photo of a broken egg with an unbroken egg, we can tell which photo must have been taken first. The arrow of time exists because entropy exists.

Summary: Our universe began in an extremely homogenous, low entropy state. Ever since the Big Bang, it has become more disordered. There are many more ways something can be disordered than ordered. Rising entropy explains the arrow of time.

V. Randomness and Quantum Mechanics

The Myth of Randomness

If you type =RAND() into an excel spreadsheet, you will get a "random" number between 0 and 1. The dirty little secret about this so-called random number generator is that there is nothing random about it. Like every other random number generator, it uses a deterministic formula to spit out seemingly random numbers. The latest version of Excel employs the Mersenne Twister algorithm, which draws from the deterministic progression of the computer system's clock.

In the 19th century, most scientists accepted the Newtonian idea that the universe was fundamentally deterministic. To the extent that there was a role for God, it was that of a "clockmaker" who set the world in motion but did not intervene in how events unfolded.

The advent of quantum mechanics complicated this picture. Quantum mechanics is a theory of how the universe operates at very small scales. While it does not explain what fundamental particles such as electrons, photons, and quarks really are, it does make incredibly accurate predictions about how they will behave. Without quantum mechanics, we would not have cell phones, satellites, or most electronic equipment.

Probabilities and Quantum Mechanics

At the quantum level, the position and velocity of a particle exist in a fuzzy haze. Before an observation is made, the best one can do is calculate the probability of it being either here, there, or somewhere else.

The Schrödinger equation, formulated by Erwin Schrödinger in the 1920s, yields this set of probabilities. The equation itself is entirely deterministic. If you know the probability distribution (or "wave function") of a particle today, you can compute its probability distribution at any point in the future.[4]

As Max Born demonstrated shortly after Schrödinger published his equation, the probability of finding a particle at a particular point can be calculated as the square of the amplitude of the particle's wavefunction at that point.[5]

Trouble in Copenhagen

Nearly one hundred years since quantum mechanics was formulated, physicists continue to debate how to interpret these probabilities, and whether it makes sense to think of them as probabilities at all.

One school of thought, the Copenhagen interpretation of quantum mechanics, treats probability as an abstract concept describing where a particle *could* be. According to this interpretation, the act of measurement forces particles out of their wave-like trance and gives them a definite reality.

A glaring problem with the Copenhagen interpretation is that it does not specify what constitutes a quantum measurement. Does a conscious observer need to perform the measurement, or will a piece of machinery suffice? "Is the Moon not there when I am not looking at it?" Einstein once asked. Proponents of the Copenhagen interpretation have never offered a satisfactory answer.

Another problem is that abstract concepts such as probability distributions should not influence physical objects such as elementary particles. Yet, in practice, they do.

The Double-Slit Experiment

Consider the classic double-slit experiment where light is shined at two slits in an otherwise opaque barrier, with some photographic film placed behind the barrier (**Figure 5**). If one were to cover, say, the right slit, the light passing through the left slit would create a fuzzy blackened band on the photographic film. Likewise, if one were to cover the left slit, the passing light would create a blackened band behind the right slit. So far, so good.

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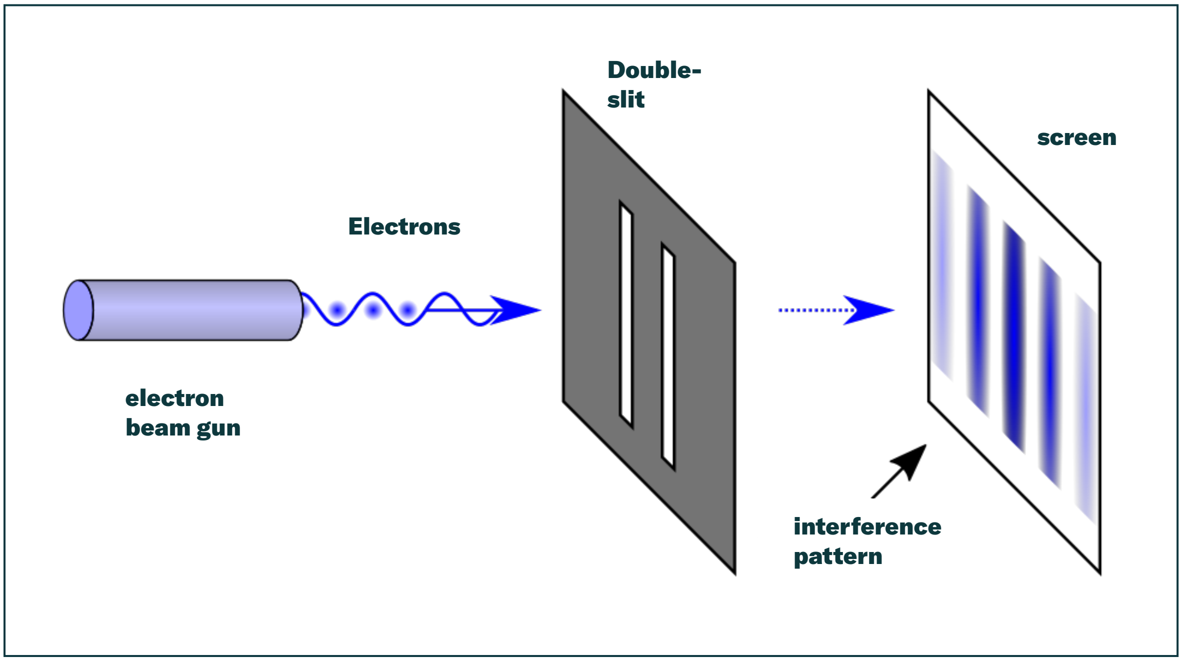
4 The Schrödinger equation is a linear partial differential equation. It is typically written as a "Hamiltonian" on one side of the equation, corresponding to the total energy of a quantum system, and a term describing how fast that system evolves on the other side of the equation. It is worth noting that the net energy of the universe is close to zero, and may be exactly equal to zero, because while matter and radiation make a positive contribution to the energy balance of the universe, gravity makes a negative contribution. Thus, for the universe as a whole, both sides of the Schrödinger equation may be equal to zero, which is another way of saying that the universe may be static. For observers such as us, however, who have positive mass and energy, it does seem as though the universe is evolving in time.

5 While the idea of taking the square of the wave function may seem odd, it is just a simple application of Pythagoras' theorem. One can think of the wave function as a vector of unit length which evolves deterministically according to the Schrödinger equation. We can decompose this vector into how far it extends along the x-axis and y-axis (or any number of dimensions, for that matter). Thus, it follows that $1=x^2+y^2$, where x and y represent the two branches of that wave function.

FIGURE 5
The Double-Slit Experiment



SOURCE: EN.WIKIPEDIA.ORG.

Now, here is the amazing part: If one were to keep both slits open, rather than seeing two blackened bands behind each slit, one would see a series of light and dark bands resembling the stripes of a zebra. In fact, there would be some areas on the film that would be more blackened if one slit were open than if two slits were open. As Brian Greene wrote in his wonderful book, *The Hidden Reality*, it is as if you have been going to your office through the same door for years, only to discover that when management opens a second door, the first door no longer provides a route to your office.

How can opening up a second slit in the barrier *reduce* the amount of light that passes through to the photographic film? The answer lies in the concept of "interference." When two water waves collide, they create a pattern of peaks and valleys. If the peak of one wave meets the peak of another wave, the result is a larger peak (i.e., constructive interference). If the valley of one wave meets the valley of another wave, the result is a deeper valley (i.e., destructive interference). If a valley meets a peak, the two waves cancel out.

One might think that what is happening in the double-slit experiment is that different photons are interfering with each other. However, this is not correct. If one were to slow down the experiment so that only a single photon was fired every second or so, one would still get the same sequence of darkened bands as when a bunch of photons were fired at the same time. Thus, it is not that one photon is interfering with another photon. It is that one photon is interfering with itself.

When a single photon goes through a slit, countless other "phantom photons" go through the same slit, and any other slit, in the barrier. What can we say about these phantom photons? Aside from the fact that they are invisible, they seem to behave exactly like real photons. They jostle the real photon around, creating interference patterns in the process.

The Many-Worlds Interpretation of Quantum Mechanics

Where are these phantom photons located? As Hugh Everett first suggested in the 1950s, the mathematics of quantum mechanics offers an answer: They are located in parallel universes. What is a real photon in one universe is a phantom photon in another universe. The whole collection of universes resides in a higher-dimension construct known as "Hilbert space."

The use of the word "space" in this context can be confusing because people tend to think of physical space when they hear the word space. The space in Hilbert space is a mathematical construct – it denotes the "space of possibilities." The parallel universes in Hilbert space do not exist in a physical space; physical space exists in them.

Everett's Many-Worlds Interpretation of quantum mechanics resolves the vexing question of what actually happens when wave functions collapse. They don't collapse. Everything that is physically possible is realized in a different branch of the wave function, but due to a process called quantum decoherence, you are only aware of what happens in your branch.

The Many-Worlds Interpretation is the simplest mathematical formulation of quantum mechanics. Multiple universes are the default in quantum mechanics. To get rid of them, one needs a theory of "disappearing universes." While many attempts have been made to formulate such a theory, the resulting work has invariably made the interpretation of quantum mechanics more mathematically cumbersome.

The Quantum Mechanical Arrow of Time

If you saw an ant crawling up a tree, you could determine the sequence of branches it must have scaled to reach its location. However, you would not be able to predict its future direction. This is simply because there is only one way to go down a tree but many ways to go up.

The universe is much like that tree. The future is unpredictable not because the future does not exist but because there are many different ways it can unfold.

In the quantum multiverse, the total number of universes does not increase over time. Rather, it is the number of *distinct* universes that increases.

The early universe was in a "superposition" of many universes. As time went by, the universe kept splitting and splitting, creating different variants of itself. Just as the branches of a tree become thinner and thinner the higher up one goes, the branches of the quantum multiverse get thinner as time passes.

If the universe is constantly splitting, then as a member of the universe, you must be constantly splitting as well. At this very moment, there are trillions and trillions of identical versions of you. As time goes by, these versions will split further apart. At first, most of the differences between you and your twins will be too subtle to notice. Over time, however, they will snowball into completely different destinies.

Are the Quantum and Cosmological Multiverses Two Sides of the Same Coin?

In Section II, we discussed the cosmological multiverse, noting that your nearest twin probably lives a googolplex meters from you. While it may seem that the cosmological multiverse and the multiverse produced by the Many-Worlds Interpretation of quantum mechanics are quite distinct from one another, there are deep connections between them.

Jaume Garriga and Alex Vilenkin have shown that both multiverses generate the same history of events. Intuitively, one can see why: When inflation began, the universe was in a superposition of all possible initial conditions. The actual distribution of matter in our observable universe reflects one particular set of initial conditions, that is, one particular branch of the wave function of the universe – the very same wave function that produces the quantum multiverse.

Yasunori Nomura and a number of other physicists have taken this idea further: They argue that the cosmological multiverse and the quantum multiverse are really the same thing.

The idea of "complementarity" – the notion that two seemingly distinct phenomena can be viewed as two sides of the same coin – is an old one in physics. It underpins the idea that one can think of an electron as a particle or a wave, but not as both. It also underpins the idea that one can think of an object falling into a black hole from the perspective of a distant observer, who will see the object freeze in time as it approaches but never quite pass the black hole's event horizon, or from the perspective of the object itself, which crosses the event horizon with no fanfare whatsoever.

Just as a black hole has an event horizon, so does our observable universe. Since space is expanding, there is a spherical horizon encompassing our observable universe, beyond which everything is receding from us faster than the speed of light.[6] As an object approaches this horizon, it will seem to someone on earth that it becomes frozen in time, similar to what an external observer sees when an object falls into a black hole.

From this perspective, one can think of all the other cosmological universes as being embedded in our own universe's cosmic horizon. If one then invokes the holographic principle, which says that everything around us is encoded on a distant two-dimension surface surrounding our universe, one can speculatively postulate that what we regard as the quantum multiverse is merely a projection from that cosmic horizon.

Summary: Quantum mechanics implies that an elementary particle can be in more than one place at the same time. Since your body is composed of elementary particles, you can be in more than one place at the same time. The Many-Worlds Interpretation of quantum mechanics suggests that the universe is constantly branching, creating an ever-larger number of distinct versions of you. There are deep connections between the cosmological and the quantum multiverse, so much so that some have speculated that they are two sides of the same coin.

6 Nothing can travel faster than the speed of light through space, but there is no limit to how fast space itself can expand.

VI. A Universe Built from Math

Numbers All the Way Down

In his essay, "The Unreasonable Effectiveness of Mathematics in the Natural Sciences," Eugene Wigner argued that mathematics has repeatedly shed light on phenomena that once seemed completely non-mathematical in nature.

The idea that a string of zeros and ones could produce an image, or a melody, would have seemed preposterous to most people a century ago. Yet, with the dawn of the digital age, we no longer give it a second thought.

Galileo helped usher in the Scientific Revolution by showing that the motion of a projectile – say, a cannonball – followed a parabolic orbit. However, Galileo had no idea why the cannonball was black or why it was hard. Today, thanks to Maxwell's equations and the equations of quantum mechanics, we can answer these questions.

Are You Made from Math?

Your body is composed of elementary particles such as electrons and quarks. These particles have certain properties such as mass, spin, and charge. The spin of an electron, for example, is ½, while its charge is -1. We attach physical representations to these numbers, but they are still just numbers.

Quantum field theories teach us that particles can be thought of as vibrations in fields that pervade space. Examples include the electromagnetic field which produces photons (aka light) or the six quark fields. But what is space? As Einstein showed, physical space can also be described purely in mathematical terms using concepts such as dimensionality, topology, and curvature. Everything seems to be mathematical at its core.

Tegmark's Mathematical Universe Hypothesis

Max Tegmark has pushed this idea to its logical conclusion. In his ground-breaking book, Our Mathematical Universe, he argues that mathematics not only describes the universe, but that our universe *is* a mathematical structure.

Stephen Hawking famously asked "What is it that breathes fire into the equations and makes a universe for them to describe?" If Tegmark is correct, the answer is "nothing." In the mathematical multiverse, all self-consistent mathematical structures exist.

Platonic Reality

The notion that mathematical structures are discovered rather than invented goes at least as far back as Plato. Plato himself discovered what we now call the five platonic solids: The tetrahedron, the cube, the octahedron, the dodecahedron, and the icosahedron (**Figure 6**). There are only five of these platonic solids – not six, not four, and most importantly, not zero.

The fact that there are exactly five platonic solids and not zero sheds light on the age-old question of why there is something rather than nothing. As philosopher and science writer Jim Holt has argued, if there

FIGURE 6
The Platonic Solids

were truly nothing, then there would be no laws. If there would be no laws, everything would be permitted. If everything were permitted, nothing would be forbidden. Hence, logically, nothing cannot exist.

The platonic solids are too simple to contain self-aware mathematical substructures such as human beings. However, there are other structures that are conceivably up to the task. The Lie group E8, for example, appears to incorporate several critical aspects of the standard model of particle physics. Stephen Wolfram's hypergraphs, which are reminiscent of John Conway's "Game of Life," can also produce wondrously complex emergent phenomena using a few straightforward updating rules.

How Elegant is the Universe?

Our universe contains some beautiful properties. One of them is symmetry. Frank Wilczek has described symmetry as "change without change." If you rotate a circle, every point on the circle will move, but the underlying object will remain the same. This is called "rotation symmetry."

As Emmy Noether first showed, every symmetry in nature is associated with a particular conservation law. The fact that energy is conserved implies that an experiment done today will yield the same result as an experiment done tomorrow (i.e., that there is no special location in time). The conservation of momentum implies that an experiment done at one point in space will yield the same result as an experiment done at another point in space (i.e., that there is no special location in space). The conservation of angular momentum implies that it does not matter if your laboratory is facing east or west (i.e., there is no special direction in space).

Not only do these symmetries give structure to everyday life, but it is doubtful that life would have evolved without them. The visual-spacial skills that humans possess would be of little use if there were no way of knowing whether a thrown ball would go up, down, or straight into your face.

Yet, despite the many elegant features of the universe, it is difficult to escape the conclusion that it could have been a lot more elegant. Why, for example, does our universe contain three "generations" of quarks (only two of which, the top and bottom quarks, are used in ordinary matter)?[7]

Figure 7 shows the so-called "Lagrangian" for the Standard Model of particle physics. Looking at this equation, one can see why Leonard Susskind has called the universe a "monstrosity" and a "Rube Goldberg machine."

The Maximal Anthropic Principle

If the multiverse is not honed for elegance, what, if anything, is it honed for? My guess is that it is honed for cranking out as many possible conscious observers as possible. The reason is straightforward: If the multiverse contains a wide variety of mathematical structures, you are more likely to find yourself in a structure that has many conscious observers rather than one that has few. We can call this proposition the "maximal anthropic principle."

The maximal anthropic principle predicts that our universe is exceedingly large, so large that the question of whether it is finite or infinite is irrelevant. No matter how large a mathematical structure one can envision, there is always a structure that is orders of magnitude bigger than that.

The maximal anthropic principle says that we can judge competing cosmological theories by the number of observers they produce. For example, we should strongly favor the Many-Worlds Interpretation of quantum mechanism over competing theories where the wave function collapses. This is not because these competing theories are necessarily wrong; there might be some universes in which versions of the Copenhagen Interpretation are correct. However, the number of observers in such universes will be far smaller than those in which the Many-World Interpretation holds.

Summary: If Max Tegmark's Mathematical Universe Hypothesis is correct, mathematics not only describes the universe, but the universe itself is a mathematical structure. This mathematical structure does not exist in time and space; time and space exist in it. Since large mathematical structures are likely to contain more observers than small structures, the maximal anthropic principle says we should assume that we are living in a structure so large that the question of whether it is finite or infinite is irrelevant.

7 This is not to say that the universe would be the same without those additional quarks. The existence of the hefty top quark may help explain why there is more matter than anti-matter in the universe. The top quark's presence also appears to explain why the Higgs field, which imbues particles with mass, has not decayed to its lowest energy potential. The universe could exist without the top quark, but it probably would not contain any observers.

FIGURE 7
Well, Obviously

$$
\begin{gathered}
\mathcal{L}_{\rm StandardModel} = \\
-\tfrac12\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac14 g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac12 ig_s^2(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar G^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac12\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac12\partial_\mu H\partial_\mu H - \\
\tfrac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac18 g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac14 g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
\tfrac14 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac12 ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
\bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\tfrac43 s_w^2 - \\
1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+ \\
\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1- \\
\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \tfrac g2\tfrac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \\
\tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- - \\
\partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y - \\
\partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) + igs_wA_\mu(\partial_\mu\bar X^+ X^+ - \\
\partial_\mu\bar X^- X^-) - \tfrac12 gM[\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H] + \\
\tfrac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \\
igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \tfrac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0].
\end{gathered}
$$

SOURCE: THECONVERSATION.COM, "EXPLAINER STANDARD MODEL OF PARTICLE PHYSICS," AUGUST 24, 2021.

VII. Personal Identity

An External Observer Looks In

Imagine floating in the void, observing the multiverse from afar. Every moment of your life, from the day you are born to the day you die, is permanently etched in spacetime. In this structure, there are many copies of you as a newborn baby. They all start their lives the same but then, their experiences begin to diverge from one another. In some versions, you remained in the country in which you were born. In others, you moved to a different country, causing you to lead a completely different life.

If the maximal anthropic principle holds, no matter how many distinct versions of you evolve from that baby, there will always be an arbitrarily large number of versions of you that are exactly the same as you are now.

Suppose there is a technology that could swap every particle in your brain with every particle in one of your identical twins' brains. Would the universe be any different after this operation were performed? The answer is "no."[8]

There is no difference between an electron on earth and one trillions of light years away. Just like swapping the number "4" from one location to another within the number *pi* would not change the number, swapping particles with your identical twin would leave the universe completely unchanged.

This leads to a radical conclusion: From an external perspective, the distinction between you and your twins is a mirage. Your twins are not your twins; they are all you.

Do Slight Differences Matter?

Suppose your twin is almost, but not exactly, like you. Would the argument that your twin is really you still hold? I think it would, as long as the differences do not alter our sense of personal identity.

The atoms in your body today are not exactly the same as the ones in your body a week ago. Yet, most people would still regard themselves as the same person that they were a week earlier. What ultimately matters, as the philosopher Derek Parfit has agued, is psychological continuity – that you and your twin feel that you are the same person.

Family, friends, and career clearly represent aspects of one's personal identity. The color of the socks one chose to wear today probably is not. Just as we can talk about concepts such as "young and old," even though there is no precise boundary between the two, we can talk about what is relevant to personal identity while still allowing for a large gray area.

[8] This, of course, is just a hypothetical example. In practice, such an operation would not be possible due to the quantum no-cloning theorem. In order to swap particles between two identical observers, we would first need to know the location and velocity of each particle. However, the Heisenberg uncertainty principle says that this is impossible since the more you know about the location of a particle the less you can know about its velocity, and *vice versa*. That said, as discussed in the text, a plausible definition of personal identity does not require an identical configuration of particles, which renders the no-cloning theorem irrelevant. It should also be noted that the Heisenberg uncertainty principle is a statement about what we can and cannot know as observers embedded within the universe. An external observer may be able to know the exact position and velocity of every particle (see Laplace's demon, for example).

The Cosmological Personal Identity Thesis

Referring back to the discussion of the block universe, we can formalize the concept of personal identity by invoking what I shall call the Cosmological Personal Identity Thesis. The thesis comes in two forms: The strong and the weak form.

The strong form says that *two observers are the same if their past world lines are exactly the same*. Swapping the particles in their brains now or at any time in their past would not change the multiverse in any way.

The weak form of the Cosmological Personal Identity Thesis says that *two observers are the same if their past world lines are the same in all subjectively relevant ways*. Swapping particles between the two observers would alter the universe. However, this action would not alter the personal identities of either observer.

Summary: From the perspective of an observer embedded in the multiverse, you and your twins are different people. However, from an external perspective, that distinction evaporates. If one were to swap all the particles between you and your identical twin, nothing about the universe would change. In that sense, your twin is simply you. The strong form of the Cosmological Personal Identity Thesis says that two observers are the same if their past world lines are exactly the same. The weak form of the Thesis says that two observers are the same if their past world lines are the same in all subjectively relevant ways.

VIII. Self-Locating Uncertainty

That Which We Do Not Know

While all your twins share the same personal identity, there could be differences among them that they are not aware of. For example, some twins, unbeknownst to them, might have cancerous tumors growing in their lungs.

Other twins might differ not in what was happening in their bodies but in what was secretly happening in the environment around them. Suppose you are walking down the street. For most versions of you, it is a safe and pleasant stroll. For some, however, danger awaits: There is a mugger lurking behind a tree.

If you were able to see the entire world line of each of your twins across the multiverse, you could tell which ones were about to encounter a mugger. However, you would still not be able to say which of those versions was really you because, until the moment you pass that tree, they would all feel like you. Physicists call this "self-locating uncertainty."

The Born Supremacy

What determines the probability of getting cancer or encountering a mugger? If you have read the earlier section on quantum mechanics in this report, you already know the answer: The Born Rule. The probability of being mugged is given by the width of the branch of the wave function that corresponds to the case where you are mugged relative to the width of all the branches in which there are observers who feel like you.

The relative frequency with which things happen – why one branch of the wave function is thicker than another – depends on entropy: The more ways that something can happen, the more likely it is to happen. Low-entropy outcomes, such as flipping a coin and getting heads ten times in a row, will occur less often than high-entropy outcomes where about half your tosses land heads and the other half land tails.

Bayes' Theorem

For simple problems where we know all the relevant information, such as calculating the probability of getting ten heads in a row, we can calculate the answer with ease. For more complicated problems, such as determining the probability of being mugged or getting cancer, where we do not have all the relevant information, we need to resort to Bayesian reasoning: You start with a prior probability and you update that prior belief using Bayes' Theorem: $P(A|B)=P(B|A)P(A)/P(B)$.

Suppose that A corresponds to being mugged and B corresponds to seeing a stranger standing in the shadows. Before you go for a walk, you think there is a 1 in 10,000 chance you will be mugged (i.e., $P(A)$=0.0001), and 1 in 20 chance of seeing a stranger standing the shadows (i.e., $P(B)$=0.05). Let us also suppose you think that one in five muggings begin with a stranger standing in the shadows (i.e., $P(B|A)$=0.2). According to Bayes' Theorem, the probability of being mugged, conditional on seeing a stranger standing in the shadows, is 0.2*0.0001/0.05=0.0004, or 1 in 2500. Thus, the sight of a stranger should lead to a four-fold increase in your subjective probability of being mugged.

It should be emphasized that in some universes you will definitely be mugged while in others you will not. In some universes you will definitely die from Covid while in others you will not. In some universes you will hit the jackpot while in others you will not. How one should make decisions in life based on this knowledge is the subject of the next few sections.

Summary: While two observers may share exactly the same personal identities, there may be differences in their environments that lead to different futures. Our lack of knowledge about where we are located in the multiverse creates uncertainty about the future. As we receive more information on their environment, we can use Bayes' Theorem to update prior credences about what is likely to happen.

IX. Life in the Cosmic Multiverse

Caring About Your Twins

We care about people we have never met, including future generations who have yet to be born. If we can care about a stranger halfway around the world, it stands to reason that we should care about our twins.

Suppose you and your spouse have been unsuccessful in having a child the natural way. You are contemplating IVF treatment. It is expensive. You would need to go into debt to do it. For some versions of you, the treatment will succeed; for others, it will fail. Unfortunately, due to self-locating uncertainty, you do not know which group you fall into.

Should the existence of the multiverse sway your decision? I think it should. In the multiverse, statements such as "we tried so hard and paid all this money for nothing" cease to be valid. If you proceed with the IVF treatment, some versions of you will succeed. To the extent that you care about how your twins feel, knowing that some will succeed should give you solace, even if you yourself fail.

Granted, the versions of you who succeed will feel sad for those who do not, possibly leaving you with the same expected utility in a multiverse as you would have in a single universe. However, even if that were so, the variance of expected utilities would still be lower in a multiverse than in a single universe. If one prefers gambles that yield a small range of possible utilities to those that yield a large range, one would be more inclined to proceed with the IVF treatment if you knew that you were living in a multiverse.[9]

Decisions Involving Low-Probability Scenarios

The example above involves a scenario where the odds of success are roughly comparable to the odds of failure. What about scenarios where the odds of success are heavily skewed in one direction or another?

Consider the following two examples:

1. You are contemplating whether to buy a lottery ticket. In a single universe, the odds of winning are very slim. But in a multiverse, some of your twins will definitely win. Are you more inclined to buy the ticket if you knew that you lived in a multiverse?

2. You are driving to an important meeting. You're running late. The traffic light is turning amber, and it looks as though some children are about to cross the road. If you stop at the light, you definitely will not make it to your meeting on time. But if you sail through the amber light there is a risk that you will hurt one of the pedestrians. In a single universe, the odds of an accident are very small. But in a multiverse, tragedy will definitely occur. Are you more inclined to drive through the amber light if you knew that you lived in a multiverse?

[9] In standard economic problems involving decisions under uncertainty, maximizing expected utility is the only thing that matters. However, one can easily envision more complicated (and more realistic) utility functions where agents prefer a smaller variance of possible utilities.

In both examples, the range of expected utilities is smaller in a multiverse than in a single universe. In a multiverse, the versions of you that lost the lottery would gain some utility from knowing that a few of your twins had won. On the flipside, the versions of you that won the lottery would lose some utility from the knowledge that most of your twins had lost.

Likewise, the versions of you that ran over a pedestrian would gain some utility from knowing some of your twins had gotten to the meeting on time. On the flipside, the versions of you who made it to the meeting on time would have to live for the rest of their lives with the knowledge that some of your twins had been involved in a horrific accident.

Even though the existence of the multiverse reduces the expected range of utilities in both examples, I strongly suspect that more people would be inclined to play the lottery, but fewer people would be inclined to drive through the amber light, if they knew they were living in a multiverse.

Why is that? The answer is that the first example involves a low probability of something good happening while the second example involves a low probability of something bad happening. If you win a lottery, you do not need to worry that your twins elsewhere in the multiverse are suffering because, realistically, most people do not dwell on having lost the lottery. Accidentally killing someone while speeding through an amber light is a different matter.

This leads to a revised conclusion: The existence of a multiverse should lead people to take on more risk, especially in cases involving low-probability, high positive-return outcomes. However, in cases involving low-probability, high-negative return outcomes, the existence of a multiverse should lead people to be more cautious. As we shall see in the final section of this report, this conclusion has important implications for investment decisions.

Cosmic Justice

In the multiverse, there is neither good luck nor bad luck. If there is a one in a million chance that you will win the lottery, then one in a million versions of you will win the lottery. If there is a 10% chance that you will get into an accident by driving recklessly, then 10% of all versions of you will, in fact, get into an accident. Statements such as "whoa, that was close" while driving are a lot less reassuring in the multiverse.

Whenever I read a story about someone who suffers an untimely death, I take comfort in knowing that in most world lines, they are still alive. At the level of the multiverse, cosmic justice reigns supreme.

Summary: The existence of a multiverse should lead people to take on more risk, especially in cases involving low-probability, high positive-return outcomes. In contrast, the existence of the multiverse should cause people to be more cautious in gambles involving low-probability, high-negative return outcomes. In the multiverse, everything happens; there is neither good luck nor bad luck.

X. Death in the Cosmic Multiverse

The End of the Line

In 1950, Albert Einstein received a letter from a grief-stricken man who had just lost his 11-year-old son to polio. “I inquire in a spirit of desperation” the man wrote, “is there in your view no comfort, no consolation for what has happened? Am I to believe that my beautiful darling child… has been forever wedded into dust, that there was nothing within him which has defied the grave and transcended the power of death?”

A few days later, Einstein wrote back, saying that our perception of life and death is an “optical delusion of consciousness.” In saying this, he was referring to the eternal existence of the block universe. Death simply marks the end of a world line. Just as a bridge does not cease to exist after you cross it, your life does not cease to exist after you die.

When Einstein wrote his letter, the study of the multiverse was in its infancy. In the subsequent 70 years, physicists discovered that world lines may branch, as in the quantum multiverse, or repeat themselves, as in the cosmological inflationary multiverse. Such processes can generate all sorts of interesting phenomena, including the subjective perception of immortality.

Subjective Immortality

Thanos is angry with you. Instead of thinking about whether the Fed will raise rates three or four times in 2022, you are reading a report about the multiverse. With the snap of his fingers, he decides to instantly kill half of all the versions of you scattered across the cosmos.

What should you expect? If you are one of the versions that is obliterated, you should not expect anything. You are dead. Only those versions of you that survive will be around to notice their good luck.

Does the Multiverse Rule Anything Out?

Imagine that you are sitting in an airplane that has experienced a critical malfunction. Both engines have exploded. The wings have detached from the fuselage. The plane is tumbling at a near 90-degree angle towards the ground. The likelihood that you will survive is very low, but is it zero?

Physicists have spent decades contemplating the existence of so-called Boltzmann brains: Human brains that could briefly form due to random energy fluctuations in deep space, complete with their own thoughts and memories. In some theories, Boltzmann brains should be a lot more common than real brains.

Just as the laws of physics do not rule out Boltzmann brains, they do not rule out death-defying scenarios in which you survive a plane crash. As long as the multiverse is vast enough to contain every possible configuration of matter – and the maximal anthropic principle says that it does – there will always be a version of you that survives the plane crash.

Death as a Process

Death usually does not occur suddenly or unexpectedly such as when Thanos snaps his fingers or your plane falls out of the sky. For most people, it is a process.

Suppose the doctor has just informed you that you have a terminal illness. The prognosis is grim. Only a small fraction of people in your condition will survive for more than a few months. What should you expect?

The answer depends on how far into the future you look. If you ask what will happen in a few weeks, you should expect to become increasingly ill. If you ask what you will perceive in a few years, you should expect to make a miraculous recovery.[10]

Afterlife and the Multiverse

What survival entails is a tricky subject. If you survive a plane crash, you are much more likely to find yourself lying in agony in a hospital than completely unscathed. You may end up wishing you had died. And if you did die, what about the possibility that you will find yourself in some sort of after-life?

Even if one is not religiously minded, the multiverse opens the door to an afterlife *via* the simulation hypothesis. In the future, our civilization or some other advanced civilization may wish to run computer simulations of the universe, complete with their own simulated beings.

Philosopher Nick Bostrom has argued that such simulations are likely to greatly outnumber "real worlds," implying that you are probably living in a simulation right now. In fact, there could be vast numbers of simulations within simulations, with today's "metaverse" being just the start of the next installment.

If the creators of these simulations follow a moral code that calls for treating simulated beings with the utmost compassion, they may create an afterlife for them.

Summary: The multiverse can generate the subjective feeling of immortality. If there is an arbitrarily large number of versions of you, some version will always survive a life-threatening event. If you are diagnosed with terminal cancer, you should expect to get increasingly sick but then make a miraculous recovery. The multiverse opens the door to the existence of an afterlife, perhaps contained within a computer simulation.

10 To drive the point further home, consider the following thought experiment. You are given a sleeping drug that lasts exactly two hours. As you are waking up, the doctor pulls a ball from an urn containing one white ball and 999 black balls. If the ball is white, you wake up to soothing music and the experiment ends. If the ball is black, you hear a horrific screaming sound over a loudspeaker, and are then immediately given an amnesia drug. The drug makes you forget that you heard the shriek. You then sleep for another two hours, after which time the procedure is repeated. The experiment continues until a white ball is finally drawn. As you fall asleep, should you assign 99.9% odds to waking up to the sound of a scream or should you assign 0%? The answer, in some sense, is both. Your immediate expectation should be to hear a scream, but your longer-term expectation should be to hear soothing music.

XI. The Measure of Existence

Don't Try This at Home

Bill is a sucker for get-rich-quick schemes. After repeated failed attempts, he finally comes up with a "can't lose" idea. Having read about the multiverse online, he buys a lottery ticket and a gun. On the night of the lottery, he recruits his ne'er-do-well friend Larry to kill him in his sleep unless he happens to be holding the winning ticket.

Let us ignore all the practical and ethical problems with this example (such as that Larry may kill Bill and abscond with Bill's winning ticket). Suppose Bill's scheme does work. Suppose there is a multiverse and the only way that Bill can wake up the next morning is if he is a millionaire.

Even then, it should be obvious that Bill's scheme is a really bad idea. By killing himself, Bill does not increase the number of moments across the multiverse where he wakes up to find that he has won the lottery; he simply decreases the number of moments where he wakes up to find he lost.

If Bill would rather be alive in a world where he lost the lottery than dead in a world where he lost the lottery, he is not doing himself any favors by proceeding with this stunt. All his scheme does is sharply reduces his "measure of existence" – the number of versions of him alive.

Conditional Versus Unconditional Probabilities

The example of Bill's get-rich-quick scheme highlights the importance of distinguishing between conditional and unconditional probabilities when making predictions in a multiverse.

If Bill's plan works as intended, he is correct to say that, conditional on having a conscious experience the next morning, there is a 100% probability that he will wake up a millionaire. However, it is equally true that only a miniscule fraction of Bill's thoughts across all his world lines will be ones where he discovers he won the lottery.

Imagine a "wandering mind" that can sample the thoughts of anyone across the multiverse. If there is a one in a million chance that Bill won the lottery, and the wandering mind decides to sample all of Bill's thoughts, it would be one million times more likely to observe Bill on the day before the lottery than on the day after.

Measure is Not the Only Thing That Matters

The discussion above underscores the fact that subjective immortality comes at a price: As you get older, the measure of your existence declines as more copies of you pass away. Subjectively, it may seem like you are immortal; but in reality, others see you die just like you see them die.

That being said, we should not overstate the importance of how many copies there are of you that feel subjectively the same as you. For one thing, even if you do not die, your measure of existence will decline as the universe continues to branch, causing versions of you that had the same past to have different futures.

Moreover, the measure of your existence can change radically depending on when you were born. For example, consider a father and his son. At the age of 15, there are many different children that the father could end up having, all of which will be born within the multiverse. However, there is only one particular father that the son could have that maintains the son's unique sense of personal identity. In other words, the father's measure of existence at the age of 15 is much higher – indeed almost infinitely higher – than the son's measure of existence at the age of 15. And yet, the son's existence is no less "real" than the father's.[11]

In thinking about the value of life, we are not just counting heads. When the Library of Alexandria burned down in 48 BC, the tragedy stemmed not from the physical destruction of thousands of scrolls, but from the knowledge they contained. If there had been another library a few kilometers away with exactly the same collection, the perceived loss would have been much smaller. Measure matters, but it is not the only thing that matters.

Summary: As you age, the number of copies of you will decline as some copies die. This is why you shouldn't be surprised that you are not 100 years old; there are just not that many copies of you in the multiverse that are this old. Still, some versions of you will live on, ensuring that the information encoded in your personal identity persists.

[11] Here, I am narrowly defining the measure of existence as the number of people who subjectively feel the same as you. One could choose a broader definition, such as the number of copies of you that are genetically the same as you. If one were to do that, the father/son example would break down. To see this point, suppose there are four different people scattered across the multiverse: Adam, Bob, Charlie, and David, all of whom have their own specific set of genes, but may have been born in different years. Bob, Charlie, and David could be Adam's son in three different universes, whereas in a fourth universe, the role of father and son could be reversed, so that, for example, Adam is David's son. If each possible combination of fathers and sons is equally represented in the multiverse, the genetic measure of existence for all four men would be the same.

XII. Existential Risk

The War That Wasn't

In the early morning of September 26th, 1983, three weeks after the Soviet military had shot down Korean Air Lines Flight 007, Stanislav Petrov received a notification from the USSR's satellite-based early warning system that the United States had launched missiles at the Soviet Union. As the duty manager in charge, Petrov was supposed to notify his superiors. Standard protocol at the time was to immediately launch a counterstrike.

"The siren howled, but I just sat there for a few seconds, staring at the big, back-lit, red screen with the word 'launch' on it," he later recounted. "A minute later the siren went off again. The second missile was launched. Then the third, and the fourth, and the fifth. Computers changed their alerts from 'launch' to 'missile strike'." "All I had to do was to reach for the phone; to raise the direct line to our top commanders - but I couldn't move. I felt like I was sitting on a hot frying pan." "Twenty-three minutes later I realised that nothing had happened. If there had been a real strike, then I would already know about it. It was such a relief."

Collective Subjective Immortality

Armageddon was averted because Stanislav Petrov did not pick up the phone. Or was it? In the previous section, we described how the multiverse creates the subjective feeling of immortality for individuals facing life-threatening dangers. The same is true at the collective level. In some parts of the multiverse, Petrov did call his superiors. However, in those parts of the multiverse, you are probably not reading this sentence.

The case of Stanislav Petrov raises a worrying possibility: Are we understating the existential risks facing ourselves and the rest of humanity? On this score, there is both good and bad news.

The good news is that the fraction of earths across the multiverse that have been wiped out by nuclear war is probably not that high. To see why, suppose that there had been a 10% chance of an all-out nuclear war in every year between 1950 and 1990. The probability that the world would have gone 40 years without a war is 0.9^{40} or about 1.5%. In such a multiverse, there would be many more people around in 1950 than in 2021. Since you are reading this report in 2021, you should conclude that it is highly unlikely that the probability of a nuclear war during that era was anywhere close to 10% per year.

The bad news is that the discussion above begs a follow-up question: Why are you reading this report in 2021 and not in, say, 2321? The Industrial Revolution began just a few centuries ago, a blink of the eye in human history. What are the odds that you were born at the dawn of the modern era rather than in the distant future when humanity has spread out throughout the cosmos?

Physicist Brandon Carter was the first person to seriously consider this question in the 1970s. Philosopher John Leslie subsequently developed it in what is now known as the Doomsday Argument. Nick Bostrom then expanded and clarified many of the key conceptual issues surrounding the topic of anthropic reasoning.

The Doomsday Argument

Imagine that two indistinguishable urns are placed in front of you. One urn contains ten balls numbered 1 through 10, while the other urn contains a million balls numbered 1 through 1,000,000. Without any further information, the best you can say is that there is a 50-50 chance that either of the two urns contains the smaller number of balls.

Suppose you dip your hand in an urn and pull out a ball numbered "7." What are the chances that you chose the ball from the urn with the smaller number of balls? The standard Bayesian updating equation says that the probability should be revised to 0.1*0.5/(0.1*0.5+0.000001*0.5)=99.999%. In other words, the evidence from this one observation allows us to move from a prior probability of 50% that the urn contains the smaller number of balls to a posterior probability of 99.999%.

Let us now change the example a bit. Instead of two urns, suppose we have two hypotheses: The first is that 200 billion humans will be born in our particular region of space. The second hypothesis is that 200 quadrillion humans will be born.

Most estimates suggest that about 100 billion humans have been born so far on earth. If fertility rates stabilize at an average of two children per woman, the total number of people to have ever been born will double from current levels by 2790. This provides a median estimate for when doomsday will occur. The true date may be a lot earlier than that if, as is likely, we are living in an exceptionally dangerous period right now due to the development of super-intelligent AI.

Summary: Just as the existence of the multiverse creates the subjective impression of immortality at the individual level, the same observation selection effect occurs at the collective level. If there are many earths scattered across the cosmos, and some are wiped out, only the people on the earths that are spared will be alive to notice. The fact that you were born just a few hundred years after the start of the Industrial Revolution raises the odds that most future earths will be destroyed.

XIII. Financial Implications

At BCA Research, we often distinguish between "forecast" and "strategy." A forecast is simply a statement about what you think is most likely to happen: *The economy will strengthen; Inflation will rise; The US dollar will weaken*, etc.

Strategy is more holistic. It considers the balance of risks to any particular forecast. It also takes into account how changes in one part of an investor's portfolio may affect other parts.

This report suggests that the entire notion of a forecast may be flawed. If we live in a deterministic multiverse, everything that can happen does happen. The best one can do is make a statement about the possible distribution of outcomes, and then update that statement using Bayes' Theorem as new information is acquired.

Thus, will the stock market go up, go down, or be flat next year? The answer to all three questions is "yes." You will experience all three outcomes. However, due to quantum decoherence, if one version of you experiences a particular outcome, then that same version of you cannot experience the other outcomes.

Although you and your twins will never meet once the wave function splits, you might still care about what happens to them. All things equal, the existence of the multiverse should make you more likely to take on risk, especially in cases involving low-probability, high-return outcomes. This should cause one to own more speculative stocks than they otherwise would.

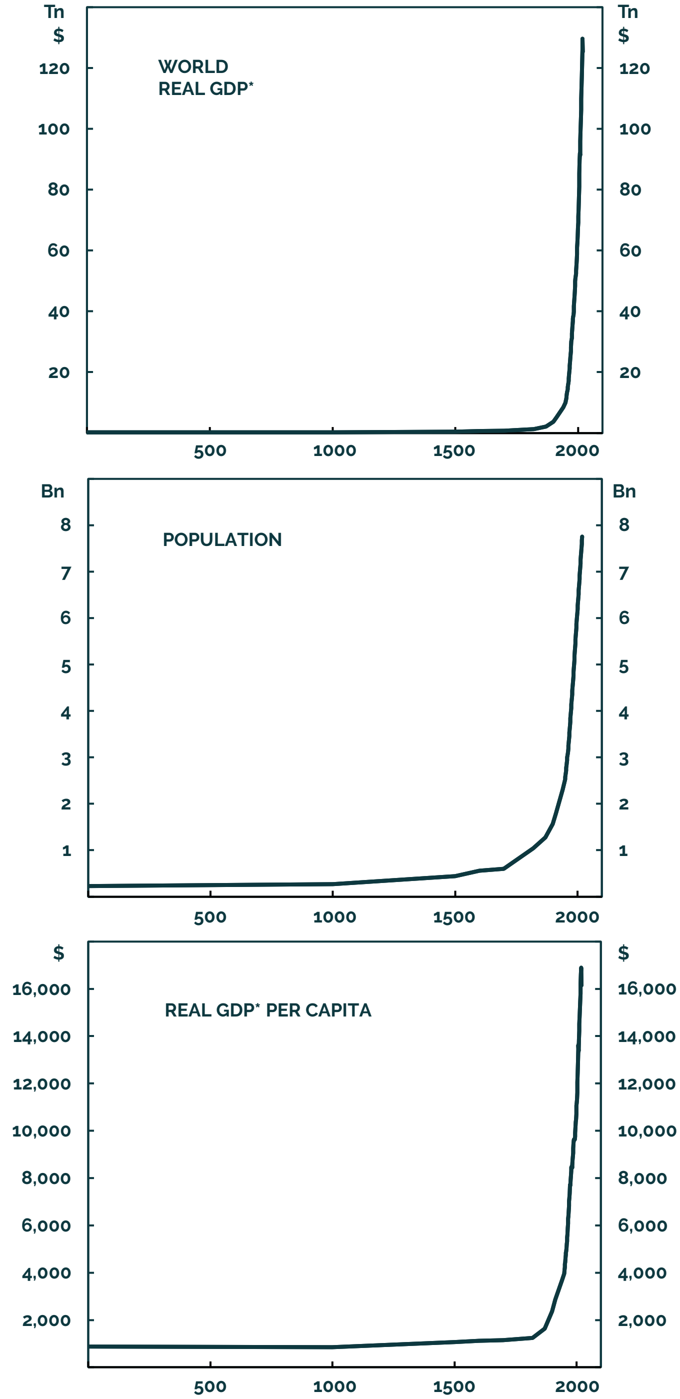
The observer selection effects produced by the multiverse pushes the idea of survivorship bias in finance to a whole new level.

Real global GDP has increased almost 100-fold over the past 200 years (**Figure 8**). Labor productivity has risen 13-fold over that period. US stock prices have delivered a real total return of 7.1% since 1871.

There was nothing inevitable about this rise in equity prices. Any number of things, including World War III, could have led to a much less favorable outcome for investors. Except you probably would not be reading this report if the US and the Soviet Union had lobbed nuclear weapons on one another. You probably also would not be reading this report if Covid-19 turned out to be more like MERS, a coronavirus that kills 40% of everyone it infects. Although we would not go so far as to say that the multiverse can fully explain the equity risk premium, its existence has probably helped flatter stock returns.

Perhaps the most controversial aspect of this report is the suggestion that the observer selection effect extends down to the individual level, so much so that it produces a subjective sense of immortality. This is not to say that you should not write a will or buy life insurance. Almost all versions of you will die. But those versions of you that survive will perceive a strange sense of good luck. That luck will only intensify as you get older and more life-threatening situations arise. New medical discoveries will suddenly appear. Technological change will accelerate. Tech stocks will boom. Things will feel a bit like they do today.

FIGURE 8
Economic History In One Chart



* DENOTES PPP GDP AT CONSTANT 2017 INTERNATIONAL $.
SOURCE: WORLD BANK AND MADDISON PROJECT.
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Summary: The multiverse diminishes the value of point forecasts, as anything that can happen does happen. Investment strategy needs to incorporate all possible outcomes, not just the most likely ones. The multiverse helps explain why stocks have performed well and why they will continue to outperform over the long haul, at least from your subjective perspective. As you get older, technological change will accelerate, with new life-saving innovations arriving just when you need them.

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