COVER STORY

MAPPING THE MULTIVERSE

THE MOST CONTROVERSIAL IDEA IN PHYSICS HAS LEAPT FROM NICHE ACADEMIC CIRCLES TO HOLLYWOOD BLOCKBUSTERS — BUT PHYSICISTS ARE STILL FIGHTING ABOUT IT.

BY DAN FALK

IN THE *STAR TREK* episode “Mirror, Mirror,” which first aired in 1967, Captain Kirk and crew must escape from a parallel universe before being discovered by their nefarious counterparts.

IF YOU LIVE ON THIS PLANET — AND YOU’RE OF A CERTAIN AGE — THERE’S A DECENT CHANCE YOU’VE SEEN THE CLASSIC *STAR TREK* EPISODE “MIRROR, MIRROR,” IN WHICH CAPTAIN KIRK AND SEVERAL MEMBERS OF THE *ENTERPRISE* FIND THEMSELVES IN WHAT APPEARS TO BE A PARALLEL UNIVERSE.

The trouble starts when they attempt to beam up from a planet during an ion storm. Something goes wrong. They appear aboard the *Enterprise*, but things are askew: Crew members greet the captain with Nazi-style salutes, and First Officer Spock sports a goatee. Observing these small but significant differences, Kirk muses that the crew has materialized in “a parallel universe coexisting with ours on another dimensional plane.”

These days, one parallel universe is hardly enough for science fiction. Instead, it seems the entire multiverse is having its Hollywood moment. Films like *Doctor Strange in the Multiverse of Madness* and *Everything Everywhere All at Once* entice the viewer with multiple versions of various characters and a dizzying array of alternate realities. Though they’re not particularly heavy on the physics, these films are definitely latching onto something. The idea of the multiverse — the provocative notion that our universe is just one of many — has fully cemented itself in mainstream pop culture. (Or, at least, in the current phase of the Marvel Cinematic Universe.) Its appeal as a storytelling device is obvious. Just as time travel allowed Marty McFly to experience different timelines in the *Back to the Future* series, multiverse tales allow characters to explore a multitude of worlds with varying degrees of similarity to our own, as well as altered versions of themselves.

While Hollywood can’t seem to get enough of the multiverse, it remains deeply controversial among scientists. Ask a prominent physicist whether they believe in a multitude of universes beyond our own, and you’ll get either a resounding yes or a vehement no, depending on whom you encounter. Advocates on the two sides show no mercy toward each other in their books, on their blogs, and, of course, on Twitter. But physicists didn’t pull the idea out of thin air — rather, several distinct lines of reasoning seem to point to the multiverse’s existence, bolstering the idea’s merit. Sabine Hossenfelder, a theoretical physicist at the Frankfurt Institute for Advanced Studies, has called the multiverse “the most controversial idea in physics.”

The debate over the existence of unseen universes may seem rather pie-in-the-sky. After all, how could worlds that we can never visit — or even detect — possibly affect anyone’s life? But the stakes are higher than they appear: Critics caution that legitimizing the multiverse could make it harder for the public to distinguish science from speculation, making it more difficult to keep pseudoscience at bay. (If scientists can’t agree about how many universes exist, how can the public be sure there’s a consensus on the reality of climate change, or the efficacy of vaccines?) Writing in the journal *Nature* in 2014, physicists George Ellis and Joe Silk describe the debate over the multiverse as a “battle for the heart and soul of physics.”

Philosophers have pondered a multiplicity of worlds at least since the ancient Greeks. But it was only in the 20th century that astronomers and physicists began to talk about multiple universes in the terms we use today.

PREVIOUS SPREAD: KELLIE JAEGER/DISCOVER. THIS PAGE, FROM LEFT: PARAMOUNT/COURTESY: EVERETT COLLECTION (2); CBS PHOTO ARCHIVE/CBS VIA GETTY IMAGES. FILM STRIP: SIMBERT BRAUSE/SHUTTERSTOCK.

MATTHIEUCLOUIS/DREAMSTIME. GEOMETRIC BACKGROUND: AMTITUS/ DIGITALVISION VECTORS VIA GETTY IMAGES

In the 1920s, astronomers found that distant galaxies are moving away from each other, implying that the universe itself is expanding. If you ran a recording of the history of our cosmos backwards, the galaxies would be seen rushing toward one another. The inescapable conclusion was that, in the remote past, the universe was much smaller, denser, and hotter. This discovery gave rise to the Big Bang model of cosmology, which describes how the universe evolved over the past 13.8 billion years from an ultra-dense blazing fireball to the enormous and vast expanse we know today.

The first pathway to suspecting there might be a multiverse emerged when scientists found problems with this original Big Bang model. The universe today is highly structured. Matter has clumped together to form stars, planets, and galaxies, while the space between these objects is nearly empty. And yet under the Big Bang model, the very early universe is believed to have been incredibly homogeneous, with every part just about as hot and dense as every other part, like a cup of hot chocolate that’s been thoroughly stirred.

So how did today’s clumpy, structured universe come about? In the 1970s and ’80s, a handful of physicists, led by Alan Guth, Andrei Linde and Alexei Starobinsky, put forward a modified version of the Big Bang, known as inflation. In the inflation model, some tiny bit of space-time underwent a stupendous (if brief) growth spurt, lasting no more than a trillionth of a trillionth of a second. This exponential expansion enlarged miniscule variations in the distribution of matter throughout the universe. Over time, those variations grew to be the galaxies and clusters of galaxies that now pepper the cosmos, containing within them countless stars and planets.

But if inflation could blow up one bit of space-time, why not many bits of space-time? Why shouldn’t inflation be happening continuously, creating new universes all the time? There didn’t seem to be any way to constrain inflation so that it yielded just one universe — and so the notion of “eternal inflation” was born, and the idea of multiple universes with it. In this view, little pocket universes — Stephen Hawking preferred the phrase *baby universes* — are continuously popping up, with the tally of new universes endlessly increasing. (In the context of “Mirror, Mirror,” we might imagine a universe where Spock has a full beard or mohawk, alongside an infinite number of other scenarios.)

Some physicists welcomed this multiplicity of universes. In his lecture slides, Linde, one of eternal inflation’s greatest champions, has depicted these universes as little colored spheres, bubbling up and creating new bubbles as they evolve, like a frothy pot of boiling water. He is on record as saying he’d bet his life that the multiverse is real.

Others are more cautious. Andreas Albrecht, a theoretical physicist at the University of California, Davis, who alongside Princeton University theoretical physicist Paul Steinhardt helped shape inflation into its modern form, finds eternal inflation troubling. That trouble stems from the idea of infinity itself.

To be sure, infinity is no problem for mathematicians scribbling equations on blackboards. But physicists strive to describe the real world, where one doesn’t encounter an infinite number of anything, let alone universes. “At the

THE MULTIPLE MULTIVERSES

There isn’t just one theory that suggests we live in a multiverse. In fact, physicists have found that several different ideas in particle physics and cosmology appear to point to the existence of universes beyond our own.

ETERNAL INFLATION: This multiverse model presents a world where little “pocket universes” are continuously popping into existence. It stems from the idea of cosmological inflation, which posits that the universe went through a massive growth spurt in the first moments of the Big Bang. These pocket universes grew just as ours did, and might now contain stars, planets and galaxies like ours.

STRING THEORY: In this theory, our universe is described as though made up of tiny, vibrating strings that are too small to detect. The equations of string theory have billions upon billions of solutions; some physicists believe this leads to a “landscape” of different universes. The idea may be closely related to eternal inflation.

MANY WORLDS: An attempt to explain a key aspect of quantum mechanics, the many worlds theory says that the universe splits each time a quantum measurement is made. This leads to an ever-growing array of universes within a branching multiverse. The model suggests that this multiverse contains multiple copies of you, as well.

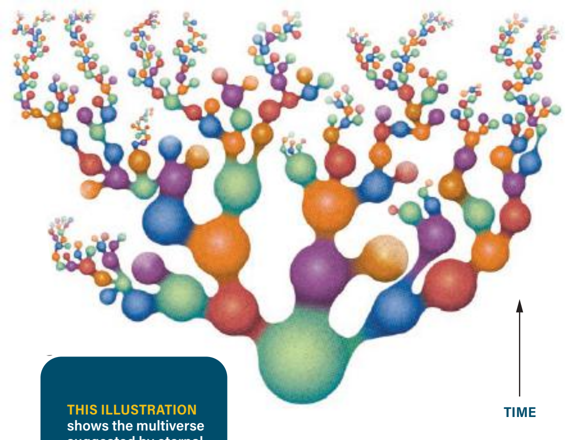
end of the day, my physics instincts pull me away from eternal inflation,” Albrecht says.

Steinhardt points to another shortcoming of eternal inflation: The theory says nothing about what any one particular universe will be like. “The problem is, now you have a theory which makes no predictions,” he says. “For any property that you can imagine, the opposite of that property also occurs, an infinite number of times.” Hossenfelder is equally skeptical: “In eternal inflation, they say they have all these universes popping up. And I’m like, well, where are they popping? Of course, no one sees anything popping; it’s just there in the mathematics.”

Through the 1980s and early ’90s, even with inflation slowly solidifying its status as the go-to model of the early universe, the idea of eternal inflation remained little more than a sideshow. Most physicists didn’t worry too much about the (alleged) extra universes. Out of sight, out of mind, as it were.

However, another idea from the frontiers of physics was brewing at around the same time — and it seemed to lend support to the many-universes idea. This new approach came from string theory, the notion that the universe is made up of tiny, vibrating strings, far smaller than anything we could see through our best microscopes, or even detect with our most powerful particle accelerators.

String theory’s equations allow for a multitude of solutions, each corresponding, physicists have suggested, to a distinct universe. And so, like eternal inflation, string theory appears to allow for a staggeringly vast array of universes. Stanford University physicist Leonard Susskind described the resulting picture as a “landscape” of universes, seemingly echoing the multiverse given by eternal inflation. In fact, many physicists believe the two ideas are intimately related. “You can’t separate them,” says Sean Carroll, a theoretical physicist at Johns Hopkins University. “One is saying that different regions, where there are different local laws of physics, can possibly exist; that’s what the string theory landscape is saying. Inflation is saying, ‘And they become real.’ ”



THIS ILLUSTRATION shows the multiverse suggested by eternal inflation, where new universes are constantly forming.

KELLIE JAEGER/DISCOVER

The multiverse controversy is rooted in the notion of testability. If we can’t interact with these other universes, or detect them in any way, some experts insist that relegates them to mere philosophical speculation. But multiverse proponents see it differently: There may be very good reasons to believe in the multiverse, they argue, even if we cannot poke at it or glimpse its many universes.

Albrecht, like many physicists, was never comfortable with the version of the multiverse suggested by eternal inflation or string theory. Still, he found himself drawn to another kind of multiverse — the one offered by the “many worlds” interpretation of quantum mechanics.

First, a Quantum 101 refresher: Quantum mechanics rests on the idea of a wave function, a kind of mathematical recipe for predicting where a particle will be, or how it will be moving, at some particular moment. Wave functions evolve over time; that evolution is governed by the Schrödinger equation, roughly analogous to Newton’s equation $F = ma$ (force equals mass times acceleration). Where Newton’s physics determines the path of a thrown baseball, Schrödinger’s equation predicts the future state of a quantum system. The catch is that we cannot know what state a quantum system is in until we measure it. Prior to measurement, it can even be in a superposition of states; that is, it’s in many states all at once. Sound familiar?

To demonstrate the principle, consider an electron. According to quantum mechanics, an electron can spin in two different ways (“up” and “down,” in physics terms). Before you look at the electron, the theory says its spin is indeterminate; it can be in both states, spin-up and spin-down. But when you actually measure the electron’s spin, the wave function “collapses,” and the superposition goes away; you’re left with one spin or the other. This view is called the Copenhagen interpretation of quantum mechanics, after the city where its first proponents, Niels Bohr and Werner Heisenberg, worked.

Some, like Erwin Schrödinger, worried about the possibility of quantum effects scaling up and impacting the

STRING THEORY’S EQUATIONS ALLOW FOR A MULTITUDE OF SOLUTIONS, EACH CORRESPONDING, PHYSICISTS HAVE SUGGESTED, TO A DISTINCT UNIVERSE.

FROM LEFT: EVERETT COLLECTION; © MIRAMAX/COURTESY EVERETT COLLECTION; © WALT DISNEY STUDIOS MOTION PICTURES/EVERETT COLLECTION

THE MULTIVERSE ON SCREEN

As the titular Doctor Strange, Benedict Cumberbatch flits between universes with ease. Mild-mannered laundromat owner Evelyn Wang (Michelle Yeoh) battles her own demons from various branches of the multiverse. Tom Holland’s Peter Parker takes a spin with alternate versions of the character from prior movies.

From *Doctor Strange in the Multiverse of Madness* and *Spider-Man: No Way Home* to *Everything Everywhere All at Once*, alternate universes are plentiful in movies today. But writers and filmmakers have been exploring the topic for nearly a century. On screen, some of these stories allude to physics; often, the parallel universes are merely imagined, playing out only in a character’s head. But these tales all capitalize on what the multiverse offers — endless chances to imagine what could (or should) have happened if things went differently.

Here is just a sampling of the many films that have toyed with the idea of multiple universes, and are well worth your time:

IT’S A WONDERFUL LIFE (1946): In this Christmastime classic, George Bailey, contemplating suicide, tells his guardian angel, Clarence Odbody, that he wishes he’d never been born. But Odbody shows Bailey an alternative universe in which he had indeed never lived — and it’s much worse. In the end (75-year-old spoiler alert), Bailey asks for his original life back.

RUN LOLA RUN and SLIDING DOORS (both from 1998): In both of these films, the central character experiences multiple timelines depending on how a specific moment unfolds. In *Run Lola Run*, it all hinges on what happens when Lola (Franka Potente) runs down the stairs of her apartment. In *Sliding Doors*, the timelines diverge depending on whether Helen Quilley (Gwyneth Paltrow) manages to board a London Underground train before the doors close.

THE ONE (2001): The multiverse figures prominently in this Jet Li action film, in which a rogue agent travels to parallel universes in order to kill other versions of himself.

COHERENCE (2013): A reunion for a group of friends goes awry when a passing comet splits reality in two. Their only hope for survival is to hunt down their multiverse doppelgängers.

DOCTOR STRANGE (2016): The film presents Doctor Strange’s origin story — and at least pays lip service to modern physics. At one point The Ancient One (Tilda Swinton) says to Strange (Benedict Cumberbatch): “This universe is only one of an infinite number. Worlds without end… Who are you in this vast multiverse, Mr. Strange?”

SPIDER-MAN: INTO THE SPIDER-VERSE (2018): This multi-dimensional take on the web-spinner features multiple Spideys from multiple Earths — including a version of the superhero as a talking cartoon pig. In 2019, it won the Academy Award for Best Animated Feature. — D.F.

everyday world — his famous alive-and-dead cat is the quintessential example. The standard view was that, if you could somehow maintain a cat in a superposition of states (current thinking suggests this would be astoundingly difficult), the wave function of the cat would collapse when observed, just as with an electron.

Some physicists find the Copenhagen interpretation unsatisfying. Why do measurements cause wave functions to collapse, and what qualifies as a measurement in the first place? Maybe, a few thinkers have suggested, the wave function doesn't collapse. Ever. Instead, when we make a measurement, the universe divides, or branches, creating a brand-new universe for each possible outcome. (Some experts caution against this phrasing as being overly simplistic, but it will do for our purposes.) When we look at that electron, the universe splits in two, with one universe containing a spin-up electron and one containing a spin-down electron. Schrödinger's cat is similarly tamed: In one universe, the cat lives; in another, it dies. These universes also contain unique copies of you — or, unique copies of universe-hopping Evelyn Wang, in the case of *Everything Everywhere All at Once*.

This many worlds view of quantum mechanics was first set out by physicist Hugh Everett in the 1950s, and has slowly gained followers in the decades since. Albrecht is one of them; he sees the idea as elegant. For him, the Copenhagen notion, with its mysterious appeal to ill-defined "measurements," is unwieldy and awkward. Plus, quantum mechanics works; it's much more than just equations on chalkboards, with actual technology like lasers, semiconductors, atomic clocks and MRI scanners to show for it. Carroll is also an ardent advocate for Everett's model, arguing the case in his 2019 book *Something Deeply Hidden*, in which he calls the theory's array of unseen universes "indisputably real."

IN THIS DEPICTION of the many worlds model, revealing the state of Schrödinger's cat splits the universe into distinct branches.

Max Tegmark, a physicist at MIT, expounded on the many worlds model in his 2014 book *Our Mathematical Universe*. Tegmark says he often thinks about the other copies of himself in those other worlds: "I feel a strong kinship with parallel Maxes, even though I never get to meet them," he writes. "They share my values, my feelings, my memories — they're closer to me than brothers."

For Hossenfelder, however, those parallel Maxes are mere fiction, along with most conjecture about the multiverse. The problem, as she sees it, is that we take the equations too seriously, a position she details in her 2018 book, *Lost in Math*. Hossenfelder takes the view of an instrumentalist, a philosophical stance that says we should take a theory seriously only if it leads to verifiable, measurable predictions. In this view, Everett's theory offers a particular mathematical approach to quantum mechanics, but says nothing about what's really out there. In Hossenfelder's eyes, Albrecht and Carroll have made the mistake of thinking that the math behind the theory is real.

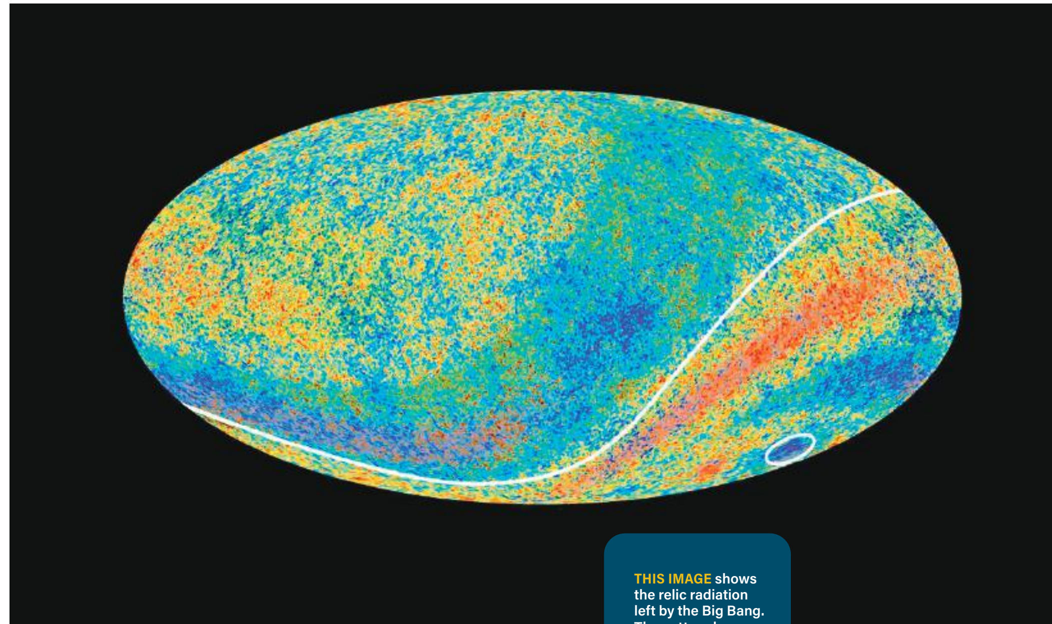
Carroll vehemently disagrees. He argues — channeling Galileo — that mathematics is the language we use to describe our physical theories; it is not some extra, added ingredient. "No one looks at F = ma and goes, 'Oh, that's mathematics, I don't trust it, I'm going to stick to physics,'" Carroll says. For him, Newton's equation is obviously physics, and so is Schrödinger's. If Schrödinger's equation predicts the existence of many worlds, so be it. If we take Newton seriously, we should take Schrödinger seriously, too.

Most physicists see Everett's many worlds as fundamentally different from those given by eternal inflation or by the landscape version of string theory. (Though a few theorists, including Susskind and Tegmark, have speculated that they may be connected.) Even so, the fact that several pathways seem to point to a multiverse suggests that the idea is worthy of such scrutiny. "Whether there's a multiverse or not does not hinge on any one theory being right or wrong," says veteran science writer Tom Siegfried, who examined the history of the multiverse idea in his 2019 book *The Number of the Heavens*. "There are different possible ways there could be a multiverse, and we don't know if any of them are correct. [...] But we have reasons to take some of these ideas seriously."

ONCE, WE IMAGINED THE EARTH AND THE SUN WERE UNIQUE; NOW WE KNOW THAT EVERY STAR IS A SUN, AND THAT MANY HAVE PLANETS ORBITING AROUND THEM.

The way Hossenfelder sees it, having a basket of speculative theories is no better than having just one. In every case, we're asked to believe in the existence of universes that we can never see or study in any way. "I'm not saying it's wrong," she says. "I'm just saying it's no longer science."

CHRISTIAN SCHIRM/WIKIMEDIA COMMONS



THIS IMAGE shows the relic radiation left by the Big Bang. The pattern has helped scientists understand the evolution of our universe.

ESA/PLANCK COLLABORATION

The controversy may sound like harmless infighting among a small group of physicists. But in their 2014 *Nature* essay, Ellis and Silk argued that if physicists aren't careful in distinguishing speculative theories from established fact, the public could be led astray. Giving credit to such speculation could "open the door for pseudoscientists to claim that their ideas meet similar requirements."

Or, as Columbia University physicist Peter Woit wrote on his blog, those who support the multiverse idea risk "turn[ing] fundamental physics into pseudo-science." For Nobel laureate physicist David Gross, invoking unseen universes to explain the properties of the one we actually see is a bit like invoking God. He once said that it "smells of religion and intelligent design."

As scientists struggle to choose between competing explanations for what they observe, a ghost often appears in the battlements — not the ghost of King Hamlet, in this case, but that of William of Ockham. The 14th-century English churchman and philosopher is best known for Ockham's Razor, which suggests that simple explanations are better than more complicated ones. Taken at face value, Ockham's approach might appear to argue against the multiverse on the grounds that it carries excessive baggage (all of those unseen universes) when we just experience a single universe. For many physicists, the argument ends there. If simpler is better, why not stick with the universe we actually see?

Except, explains Siegfried, Ockham did not merely say that simpler is better. Rather, in devising an explanation, it's desirable to use the fewest principles, even if they lead to complex results, Ockham argued. (It's no knock against, say, astrophysics, that it predicts billions of planets orbiting billions of stars.) Not only that, Ockham was actually pro-multiverse. "Ockham himself was the biggest advocate for the multiverse," Siegfried says. "He argued vigorously against all of Aristotle's objections to having more than one universe. So it's kind of ironic that people use Ockham's Razor to argue against the multiverse."

In the movie *Spider-Man: No Way Home*, there's a playful scene in which today's web-spinner, played by Tom Holland, meets parallel-universe versions of himself from earlier films, played by actors Andrew Garfield and Tobey Maguire. This is, to be sure, straight-up fiction. We have no chance of ever actually seeing the universes described by eternal inflation, string theory, or the many worlds version of quantum mechanics. That also nixes the odds of ever encountering our other selves. The odds are similarly low that the debate over the multiverse will end soon.

But history, according to Siegfried, suggests which way the wind is blowing: At one time, the only galaxy we knew of was the Milky Way; now we know that billions of other galaxies are scattered throughout the universe. Could a more expansive view of the universe itself be the next breakthrough? As Siegfried puts it: "Every time in the past that we've thought, 'We've got it; this is what the whole universe is' — the people who've said, 'Maybe there's more than one of those' have always turned out to be right." ◘

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