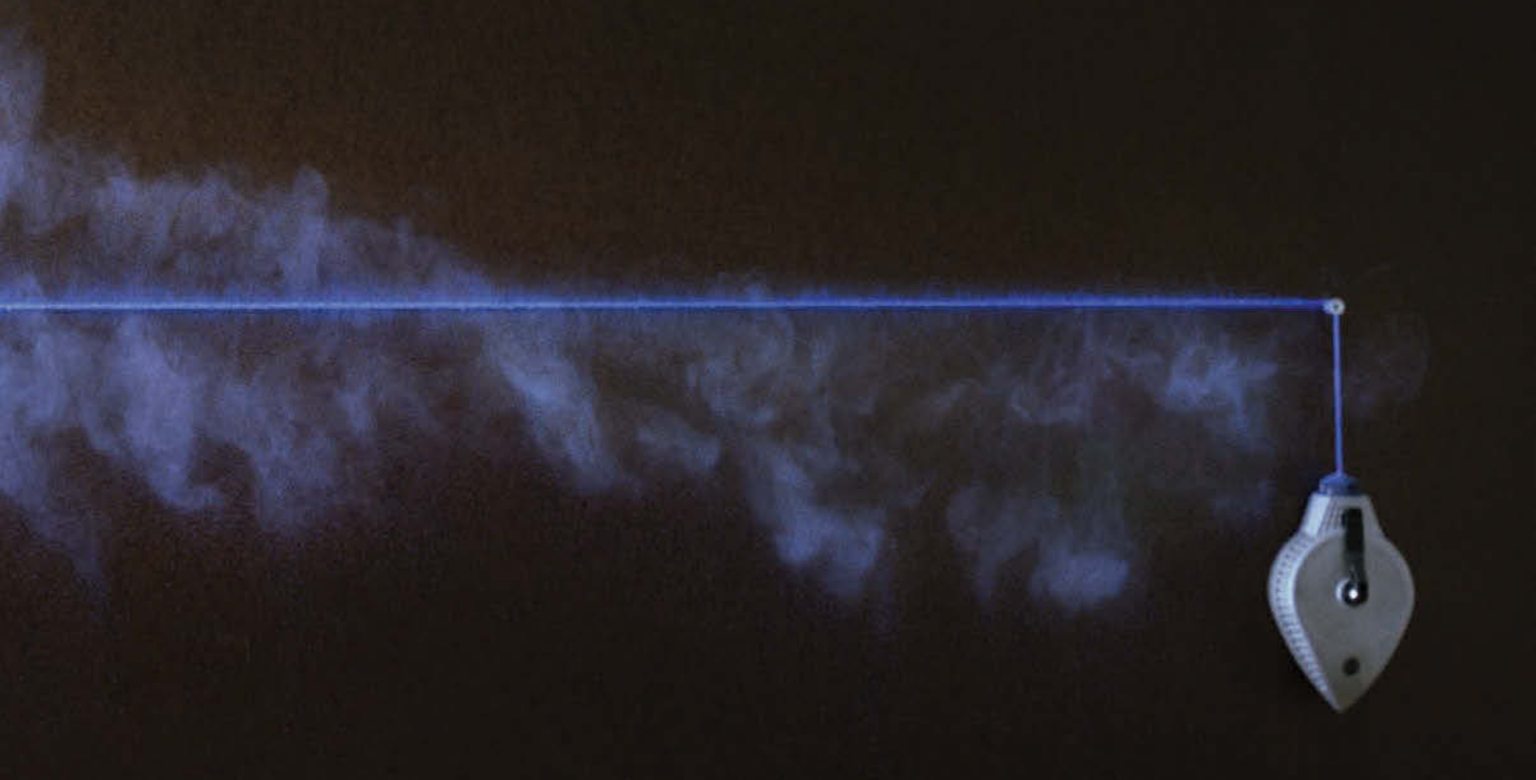
Gravity *off the* Grid

JULIAN BARBOUR CUTS AN UNLIKELY FIGURE for a radical. We sip afternoon tea at his farmhouse in the sleepy English village of South Newington, and he playfully quotes Faust: *That I may understand whatever binds the world's innermost core together, see all its workings, and its seeds.* His love of Goethe's classic poem, about a scholar who sells his soul to the devil in exchange for unlimited knowledge, is apropos. Forty years ago, Barbour's desire to uncover the innermost workings of the universe led him to make a seemingly reckless gamble. He sacrificed a secure and potentially prestigious career as an academic to strike out on independent research of his own. His starry-eyed quest: upending Albert Einstein's theory of relativity, and with it our understanding of gravity, space, and time.

It was less than a century ago that Einstein was the most radical physics thinker around. With his general theory of relativity, he discarded the traditional notion of space and time as fixed and redefined them as flexible dimensions woven together to create a four-dimensional fabric that pervades the universe. In Einstein's vision, this stretchy version of space-time is the source of gravity. The fabric bends and warps severely around massive objects such as the

From a farmhouse in the English village of South Newington, a gentleman scientist plots to upend Einstein's model of space, time, and gravity—and send physics off on a bold new course. *by* ZEEYA MERALI



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sun, drawing smaller objects such as planets toward them. The force that we perceive as gravity is the result.

Yet Einstein's fabric left a few loose threads that cosmologists have struggled to tie up ever since. For one, general relativity alone cannot explain the observed motions of galaxies or the way the universe seems to expand. If Einstein's model of gravity is correct, around 96 percent of the cosmos appears to be missing. To make up the difference, cosmologists have posited two mysterious, invisible, and as yet unidentified ingredients: dark matter and dark energy, a double budget deficit that makes many scientists uncomfortable. Einstein also failed to deliver an all-encompassing theory of "quantum gravity"—one that reconciled the laws of gravity observed on the scale of stars and galaxies with the laws of quantum mechanics, the branch of physics that explains the behavior of particles in the subatomic realm.

While other scientists tread softly around the edges of Einstein's theory, hoping to tweak it into compliance, Barbour and a growing cadre of collaborators see a need for a bold march forward. They aim to demolish the space-time fabric that stands as Einstein's legacy and remap the universe without it. This new cosmic code could eliminate the need to invoke dark matter and dark energy. Even more exciting, it could also open the door to the theory of quantum gravity that Einstein was never able to derive. If Barbour is right, some of the most fundamental things cosmologists think they know about the origin and evolution of the universe would have to be revised.

"We have radically reformulated Einstein in a different light that might be valuable for understanding cosmology and quantum gravity," Barbour says. "It is a very ambitious hope that it could play such a role."

BARBOUR'S PENCHANT FOR MAPPING SPACE and time is apparent even before we meet. His home, College Farm, is hidden away some 20 miles from the nearest city of note, Oxford. Knowing that visitors often struggle to find the 17th-century farmhouse, he has sent two sets of directions. The first includes detailed instructions for navigating through the village's rolling hills along sunken roads, passing thatched cottages, the local Duck on the Pond pub, and the ancient church near his home. Those directions might have served equally well for locating Barbour's house at the time it was built in 1659, a few decades before another English physicist, Isaac Newton, wrote his *Principia,* setting down the ideas about motion and gravity that dominated physics for almost three centuries.

In one respect Barbour has spent 40 years faithfully preserving Newton's universe, meticulously restoring the farmhouse's period features. He proudly shows me that each window frame is adorned with a small metal animal figure—a lion, a stag, a cockerel, and the flying horse Pegasus. The lion is Barbour's favorite because it is original; the rest he had specially made based on designs seen in other buildings of the same era in the village. He taps the sturdy stone wall surrounding the window. "These were here 350 years before us and our modern conceptions of physics," he tells me, "and chances are they'll still be standing 350 years after we've gone."

By contrast, the second set of directions for finding Barbour's farmhouse—GPS coordinates—work only in the modern, post-Einstein reality. The satellite navigation system pinpoints positions on Earth to within 10 meters (30 feet) in a matter of seconds by comparing the timing of signals received from a number of satellites at known locations above the globe. The system works with such stunning accuracy because it compensates for the fact that clocks on fast-orbiting satellites run at different rates from those on the ground. The fact that gravity and motion affect the flow of time was discovered by Einstein as a core element of his theory of relativity.

To remap the cosmos, Barbour has tapped into both Newton's and Einstein's conceptions of nature and then discarded key elements of both. Newton imagined that the universe was spanned by absolute space, which served as a rigid invisible backdrop or grid against which the position of all stars and planets (or farmhouses and the Duck on the Pond pub, for that matter) could be definitively located. Remove all objects from the universe and Newton's grid would remain while time ticked along at a steady universal rate, as if marked by God's wristwatch.

Einstein saw time and space as altogether more malleable. During his student days, he had studied the work of James Clerk Maxwell, a Scottish physicist who recognized the speed of light—300,000 kilometers or 186,000 miles per second—as a fundamental property of electromagnetic fields. In Maxwell's time, most physicists thought that light, like sound, needed some kind of medium for transmission; the mysterious, invisible substance they hypothesized, called the luminiferous ether, would presumably be influenced by the motion of Earth around the sun and the movement of the solar system through the galaxy, a dynamic that stood to alter the speed of light depending on the relative direction from which that light came. But numerous experiments failed to discover any evidence of the ether, and Einstein realized the speed of light must stay constant no matter which direction it came from or how an observer moved.

That understanding contradicted Newton's view of space. In his physics, you could catch up to anything, even light, if you moved fast enough. But if the speed of light holds steady no matter where you were or how you were moving, it would always seem to zoom away from you at the same constant 186,000 miles per second. Einstein enshrined that principle in his first theory of relativity (special relativity), which states that you can never catch up to a light beam no matter how hard you might try.

Barbour first heard these ideas as a teenage schoolboy in the early 1950s, a time when Einstein was still alive. As a 3-year-old child Barbour had earned the nickname "Why?" from a friend of his mother's because of his ever-curious nature. Yet upon learning of relativity, he uncharacteristically did not question it. "I was lost in admiration," he says. "Everyone thought Einstein was the greatest figure after Newton, and so I took it on trust, almost like someone being indoctrinated into a religion."

It took another decade for Barbour's questioning nature to overcome his awe. Twenty-four years old and a recent graduate of the University of Cambridge in 1961, he was planning on graduate school in astronomy. But he took a year off the academic conveyor belt to visit Germany and learn two languages: "Russian, because I adored the writer Pushkin, and German, because the first girl I fell for was a German au pair," he says with a chuckle. So taken was he with the country that he stayed on to complete an astronomy Ph.D. at the University of Cologne, gaining the mathematical and language skills to read Einstein's texts in their original German and grapple with their meaning.

What struck Barbour most was Einstein's comment that his intuitive leap about space and time had been inspired by Austrian physicist and philosopher Ernst Mach, whose study of the speed of sound in fluids helped explain the sonic boom heard when objects break the sound barrier. ("Mach numbers" are named in his honor.) Long before Einstein, Mach had advocated a "truly relative" theory, in which objects were positioned only in relation to other tangible objects—Earth relative to sun, pub

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relative to farmhouse—and not against any abstract background grid. "Mach wanted to obliterate Newton's absolute space and time, arguing that physics should not be at the mercy of an invisible grid that nobody can verify exists," Barbour says. "This informed Einstein's thinking at the time."

That Machian ideal seized young Barbour, too. "It was something in my psyche," he says. "The insight resonated very deeply with me." The more he read, the more Barbour became convinced that Einstein had failed to take Mach's ideas seriously enough. "I have certain knowledge from my readings in German," he says, "that Einstein didn't implement Mach's ideas in the most direct way because he thought that way was too hard."

Barbour felt that Einstein had taken a circuitous route to reframing the cosmos. Einstein's 1905 publication on special relativity seemed to bring him closer to Mach's camp, dismantling part of Newton's grid by abolishing the notion that time was absolute. But it did so only by linking time to the three dimensions of space to create a rigid, four-dimensional block of space-time. Then, with the broader, more all-encompassing version of relativity (general relativity) he published in 1916, Einstein reshaped that backdrop into a more malleable four-dimensional space-time. Sure, Einstein's space could be warped by the presence of massive objects, undulating like the hills of South Newington. But despite the name of his famous concept—the theory of relativity—Einstein's universe still required a background against which particles and objects could be located in both time and space. Compared to Mach's ideals, Einstein's theory was not truly relative.

By 1964 Barbour was almost finished with graduate school and knew he wanted to pick up where Mach had left off. Pursuit of Mach's concept in defiance of Einstein seemed a path to career suicide. Einstein's theories were cornerstones of modern physics, whereas Mach's ideas were largely considered historical curiosities. So Barbour decided to change the rules: Forgoing the security of an academic career, he set out on his own.

That might have seemed reckless to most graduate students, but Barbour's father had also been an independent scholar, studying Arabic and traveling through the Middle East. "He was a role model to me," Barbour says. Besides, he had a backup plan. Using his new mastery of Russian, Barbour realized he could work as a translator to pay the bills.

WITH HIS NEWLY MINTED DOCTORATE, YOUNG Barbour pressed on where Einstein had feared to tread, coming closer to Mach by dispensing not just with Newton's rigid grid but with the very concept of space-time. In general relativity, time is a dimension interwoven

Galaxy cluster Abell 1689 seems to be held together by swaths of unseen dark matter; blue shows its theoretically inferred location. But could dark matter be an illusion?

NASA

with the dimensions of space. In Barbour's universe, on the other hand, time is emergent: It is a measure of how space changes but not a fundamental component of it.

By 1969 Barbour had purchased College Farm, leaving Cologne and moving back to South Newington with Verena Bastian, his German wife. To support his growing family, including son Boris and daughter Jessica, he set up a business as a translator, drawing on his old love of Pushkin and rendering English versions of Russian scientific texts. But all the while, he tinkered away at his Machian model of the universe. "There was the possibility of a big discovery, and I had the scent of something exciting," Barbour says. The idea was regarded highly enough to make it into the pages of *Nature*, banishing any worries he might have had that by shunning academia, he would be dismissed as a crank.

From 1975 on, Barbour joined forces with Bruno Bertotti, a physicist at the University of Pavia in Italy, to take on the juggernaut that is Einstein. They developed a technique known as "best-matching," in which the motion of an object (for instance, the moon) is tracked solely by its changing distance from other objects (like the sun and the Earth), rather than its changing location against a grid. Similar to playing connect the dots to chart how the moon's position changes over a fortnight, Barbour imagines a triangle whose corners are formed by the location of the three celestial bodies at one point in time and a second triangle formed by the same bodies a moment later. Using the mismatch in the shapes of the two triangles laid one on top of the other, he can quantify the amount of change that has taken place. He even used his best-matching technique to derive Newton's laws of motion in a completely new way. He made the effort, he says, just to prove his model worked.

By 1982 Barbour and Bertotti had come up with a new theory of gravity that described the world just as accurately as Einstein's general relativity but without invoking time as a fundamental dimension.

In a sense, Barbour takes physics a step back. He begins not with Einstein's four-dimensional space-time but with a three-dimensional space vaguely resembling that of Newtonian dynamics. The space of Barbour's theory, however, is curved, bearing little resemblance to Newton's rigid euclidean grid. And in cases where Einstein's and Newton's theories differ, Barbour's shape-based calculations hew to Einstein's more sophisticated predictions. They match Einstein's explanations of everything from the bending of light by distant galaxies to the distortion of time in those GPS satellites. The added accuracy in Barbour's calculations arises from the fact that best-matching requires an accounting of the positions and gravitational influence of distant cosmic objects that Newton's equations tended to ignore. The reason Einstein's theory is so much better than Newton's, Barbour notes, is that Einstein was able to get much closer to the Machian ideal.

The success of Barbour's theory was gratifying, but it also threw him a curveball. He had set out to use Mach's ideas to topple Einstein, but his results and Einstein's seemed essentially the same. Still, Barbour remained convinced that Einstein didn't go far enough: Because relativity wasn't truly relative—or Machian—fundamental inconsistencies in Einstein's model of the universe remained. If he had stuck with the Machian approach, Einstein might have attained the all-encompassing "theory of everything" that consumed the last decades of his life. "He might have produced a version of his theory of gravity that would not conflict so fundamentally with quantum mechanics," Barbour notes. But Einstein had lost his nerve.

ONE HINT OF TROUBLE CAME TO LIGHT IN THE 1970s, when astronomers realized the outer portions of a significant number of galaxies were rotating inexplicably fast, seemingly pulled by more gravity than general relativity could explain. To account for the extra gravity, they embraced the idea of dark matter. If only they could find the missing mass, then all the accounting would fall into place and the rules of gravity would look sensible again.

But clouds of undetectable dark matter was not an entirely satisfying explanation to Hans Westman, a University of Sydney physicist who has collaborated with Barbour at College Farm. Seeking a better answer, he started analyzing a largely forgotten theory developed by the German mathematician Hermann Weyl. Around 1918 Weyl attempted to modify general relativity so that it would not require absolute measurements of scale or distance—so that it would abide by an entirely relative system, again akin to that of Mach. "Einstein called Weyl's model a stroke of genius of the first rank," Westman says. On closer inspection, though, he found the theory mathematically messy, yielding unpredictable results. In the end, both Einstein and Weyl tossed the model out.

Westman now argues that this rejection was a grievous mistake, because abolishing a scale of measurement and making everything completely relative might have enabled a different theory of gravity, possibly one that meshed with quantum mechanics and had no need to invoke the notion of dark matter at all. To determine whether a Weyl-inspired theory of the universe could explain away the need for dark matter, physicists will have to put it to the test and see if it produces a universe that looks like ours. Westman thinks it could. A theory that reproduces reality without dark matter would be much more beautiful than one with dark matter, Westman says, because we cannot make predictions based on the properties of an undetectable particle; we can only infer what dark matter must be like in order to have created the configurations we observe.

Many observational astronomers counter that the evidence for dark matter is now so strong that it will take more than a new theory of gravity to disprove it. Only more research, Westman responds, will enfranchise dark matter or cast it from the fold. The ultimate evidence would be direct confirmation of dark-matter particles by one of the specialized detectors created to seek them out.

Barbour's Machian approach could also help disprove the reality of the other dark mystery of modern cosmology, dark energy. Despite its name, dark energy is better thought of as a repulsive force that pushes galaxies apart from each other. It was first widely invoked by cosmologists in 1998 to explain why the expansion of the universe seems to be speeding up, a finding that won the Nobel Prize in Physics last year.

David Wiltshire, a physicist at the University of Canterbury in New Zealand and a visitor to Barbour's College Farm, thinks the reason dark energy is so mysterious is that it is an illusion. Wiltshire's argument is that most physicists essentially ignore one of the major principles at the heart of general relativity: that clocks in different parts of the universe can run at different rates. Einstein held that there is no such thing as universal time and that matter affects the rate at which clocks tick, such that time slows near massive objects. Accordingly, Wiltshire notes, the flow of time near galaxies could be slower than the flow of time in empty space. "In a truly relativistic view, the age of the universe differs from place to place," he says. "In empty space, over 18 billion years have elapsed since the Big Bang, but within galaxies only about 15 billion years have passed." (Because Wiltshire starts from a separate set of physical assumptions, his numbers are different from the now canonical 13.7 billion years for the age of the universe.)

By ignoring those nuances, Wiltshire claims, cosmologists have misinterpreted the positions of the distant supernova explosions used to determine how quickly the universe is expanding. Light from a supernova travels to Earth's telescopes after passing through both patches of empty space (where the universe expands more rapidly) and through intervening galaxies filled with matter (where the expansion slows). As a result, Wiltshire says, cosmologists expect supernovas to be closer than they appear, creating the illusion that the expansion of the universe is speeding up. Supernova measurements are the key

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evidence for dark energy. But Wiltshire thinks physicists may have been chasing shadows rather than zeroing in on reality for years.

PERHAPS THE MOST FAR-REACHING ASPECT of Barbour's view of gravity is that it could reconcile general relativity and quantum mechanics, the physics of the subatomic realm, marking a major step toward the long-sought theory of everything. This incompatibility tortured Einstein in his later years and has flummoxed physicists ever since. The crux of the problem is that the quantum realm of the extremely small is defined by uncertainty. Before observing a subatomic particle, there is fundamentally no way of predicting exactly where you will find it when you measure it. Quantum equations describe only the probability of finding a particle in a certain place. This fuzziness is not due to poor measurement; it is an intrinsic property of particles on the quantum scale. In many, many experiments, quantum particles, when measured, turn up in various locations with the same frequencies as predicted by their probabilistic equations.

The problem comes when theorists try to combine relativity with quantum physics. Quantum mechanics still relies on removing any obstacle to coming up with a complete theory of gravity that works in both cosmic and quantum realms.

Today physicist Sean Gryb, who recently left College Farm for a postdoc position at Utrecht University in the Netherlands, is embarking on that Machian path to the theory of everything. Gryb first learned about Barbour's gridless universe while a graduate student at the Perimeter Institute in Waterloo, Ontario, in 2008. At the time, Gryb was skeptical, to say the least: He concluded that Barbour must have made a mistake and decided to find it. So in August 2010 he joined a group of friends, including postdoc researchers Tim Koslowski, also at Perimeter, and Henrique Gomes at Imperial College London, to pick apart Barbour's writings just as the young Barbour had once scrutinized Einstein's. The students thought that their background in quantum gravity would allow them to find Barbour's misstep.

That never occurred. Instead, the work withstood their ongoing scrutiny, and last year Gryb, Koslowski, and Gomes took their first tentative steps toward developing a theory of quantum gravity. They hope to show that Barbour's model, unlike Einstein's, does not cause gravity to flare up to infinite levels in tiny regions. Without those infinities, there should be no fundamental obstacle to uniting Barbour's theory with quantum mechanics. Such a marriage could lead to astonishing new insights, like an explanation of what happens inside black holes and what conditions were like at the moment of the Big Bang, when the whole universe was born. "That's the dream we are working toward now, although the math is tough," Gryb says with a touch of understatement.

Gryb credits not just Barbour but also the idyllic surroundings of College Farm, which serves as a kind of private research campus, for inspiring the work. "The house evokes a simpler time and just opens your mind to new ideas when you visit," he says. "Some of our biggest breakthroughs come from talking while walking across the rolling fields or when cooking dinner." Indeed, Barbour continues to work from College Farm even though he is now, in a startling turn, a visiting professor at Oxford. In 2008 he won his first-ever official research grant and used the money to travel to conferences, as well as fund collaborators like Gryb and Gomes, the first two scientists to complete Ph.D.s on Barbour's shape dynamics, work that had its origin right there on the farm.

AT THE END OF GOETHE'S *FAUST*, THE SCHOLAR'S sincerity redeems him, and God saves him from the devil's clutches. Barbour is finding similar redemption in many of his colleagues' eyes. "He stands out as the soft-voiced English gentleman who makes deep points about gravity that nobody else has considered," says Olaf Dreyer, an expert on quantum gravity at the Sapienza University of Rome. "Barbour's insight could be leading to exactly the breakthrough physics needs." Even a sympathetic character like Dreyer adds a skeptical rejoinder, though: "It could just as easily be leading to a dead end."

Is Barbour, now 75, waiting to be officially vindicated? Is he amazed that so many physicists embrace what to him are clearly illusions about space and time? A gentleman to the end, he refuses to answer such pugilistic questions. Instead he comments that it could take many more years to persuade the physics community that his framework will bear fruit, but he is willing to do the work.

"Why do some people get caught by an idea that takes over your life? I don't know, but I do know that as long as it doesn't drive you crazy, it is a blessing," Barbour says gently. "When I started out on this 40 years ago, I said to my family that I know what I want to do and it will take me the rest of my life to do it—and that is the way it has worked out." ◗

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the absolute measurements of time that Einstein discarded. String theorists have tried to reconcile the differences but keep running into roadblocks: For instance, the ripples caused by uncertainty might cause such frenzied gyrations of Einstein's space-time that every location would be riddled with black holes, an impossible outcome. In other words, relativity and quantum mechanics seem to be hopelessly at odds.

"Most physicists are trained to get on with calculating things and not worry too much about these contradictions," Barbour says, but to him, they were key. In his true Machian theory, there is no space-time fabric that could be torn apart by quantum fluctuations. In fact, there is no fundamental dimension of time to create conflict between general relativity and quantum mechanics,

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