The Forgotten Mystery of Inertia

BY TONY ROTHMAN

A century after Ernst Mach and Albert Einstein cast doubt on absolute space, we still don't know how a gyroscope stays pointed in a fixed direction.

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In days of yore, at a World Science Fiction Convention in Boston, a Harvard graduate student polished his reputation as a brilliant mad scientist by roaming the convention halls, brandishing what at first glance appeared to be a rather peculiar steel bowling ball. Portholes perforated its surface, providing a glimpse of electronic hardware inside; tangled wires sprouted from the same holes, and a gear train surrounded the mysterious object’s equator.
“What’s that?” I asked him.

“It’s the gyro platform for an intercontinental ballistic missile,” he replied. “If you put it on a Titan rocket, it will fly to Kiev.”

“How do you know?”

“It’s an inertial guidance system, stupid. It knows where Kiev is.”

"I know how inertial guidance systems work, but how do you know it knows where Kiev is?"

"Oh, that. It was stamped on the box."

This sorcerer's apprentice had discovered that for $900 you could buy a surplus intercontinental ballistic missile, 10 years before the electronics were declassified. His Titan was delivered on two railway cars, "Kiev Titan Missile" stamped on the crates. He junked the body, donated the engines to an art museum, and saved the electronics for his research. A tall tale? Sounds like one, but the gyro platform was there for all to see.

I didn't understand it, nor did my mad interlocutor, and anyone who claims otherwise is not being entirely honest. Despite a gyroscope's utter simplicity—it is, after all, nothing more than a wheel on an

Illustration by Tom Dunne.

axle—it remains the most fascinating and mysterious device ever created. Spin up the wheel, place it on a pedestal, and there it stays, pointed at…?

That is the question. At what, exactly, is the gyroscope pointed? According to the law of inertia, objects tend to continue doing what they've been doing: If at rest, they remain at rest; if moving, they continue moving at the same speed in the same direction. The gyroscope also bends to inertia's will, but in confounding ways. Touch it, and the gyro opposes you by veering in unexpected directions. If it is spinning extremely rapidly, the gyroscope remains rigidly locked in the direction it has been set, its sights fixed on...Kiev—hence the term inertial guidance systems. If a rocket veers off the gyro's fixed course, a sensor detects the error, and a servomechanism realigns the missile with the gyroscope axis.
But this is just the explanation stamped on the box. What tells the gyro it is set on the Great Gate of Kiev? Isaac Newton would argue that the gyro is pointed in a fixed direction relative to "absolute space," what physicists term an inertial reference frame—indeed, the ultimate inertial reference frame. Think of it as an invisible reference grid somehow etched into the fabric of the universe. But if absolute space is a highly abstract concept, the gyro's behavior is very tangible. Set up a gyro on a lecture table at a university (or a coffee table at home), and as the day progresses it appears to rotate with respect to walls…or is it vice versa? Are the rotations relative, or are they absolute?

In his magnum opus, Principia Mathematica, Newton proposed a thought experiment to prove that rotation takes place with respect to absolute space. He imagined a bucket partially filled with water and hanging from a rope, which an experimenter has twisted up.

When the experimenter releases the bucket, the rope untwists, and the bucket begins to spin. At first the water remains flat, but as the pail speeds up and drags along the water, its surface eventually becomes concave due to the centrifugal force of the rotation. At that stage, the water and vessel are rotating together, and there is no relative motion between them. Yet somehow the water "knows" to create a concave surface.

Newton insisted that the concavity must be due to the water's rotation with respect to something else—absolute space. Rotation is absolute, not relative. That answer stood largely unchallenged for two centuries, until the Austrian physicist Ernst Mach flatly declared Newton to be wrong.

Relative Revolutions

In his 1883 book Science of Mechanics, Mach wrote that Newton's thought experiment "simply informs us, that the relative rotation of the water with respect to the sides of the vessel produces no noticeable centrifugal forces, but that such forces are produced by its relative rotation with respect to the mass of the Earth and the other celestial bodies." Mach continued, that "no one is competent to say how the experiment would turn out if the sides of the vessel increased in thickness and mass till they were ultimately several leagues thick." He dismissed absolute space as an "arbitrary fiction of our imagination."

Mach never gave a precise formulation of what became known as Mach's Principle. Nevertheless, the essential idea is simple enough. According to Mach, Newton's conception of absolute space lacks all meaning. Inertia—that tendency of massive objects to move at constant velocity—must depend on other bodies, because motion itself must be measured relative to other bodies. Rotations and accelerations along straight paths take place with respect to the reference frame of the distant stars and galaxies. The centrifugal forces that throw you to the side of an automobile as it rounds a corner arise because you are accelerating with respect to the distant matter in the universe.

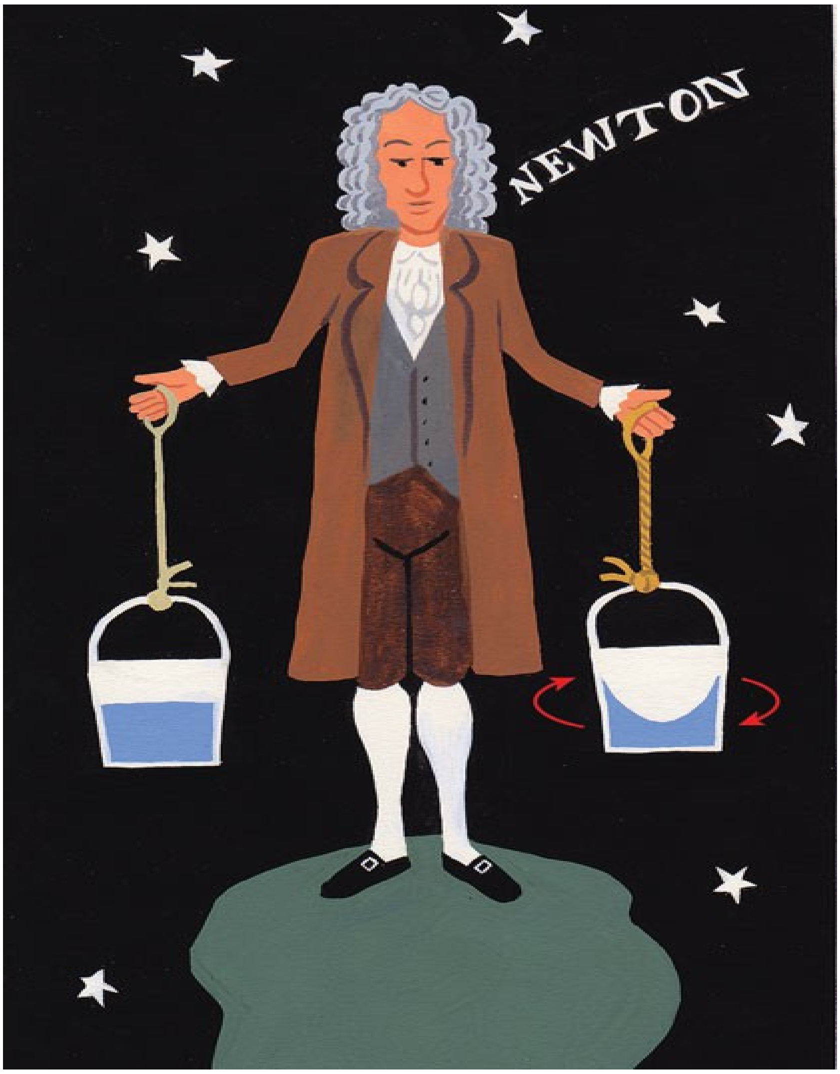

Illustration by Tom Dunne.

Reframed as a question, no proposition goes straighter to the fundamentals than Mach’s Principle: Would you feel centrifugal forces in an empty universe? Does the law of inertia mean anything in an empty universe? Mach would give a resounding “no” to both questions: Inertia is not a property intrinsic to an object but depends upon all the mass in the universe. Mach's suggestion proved heretical, not least because Newton's laws, with their assumption of absolute space, work so exquisitely. It furthermore went against our human intuition that our experience of the world is fundamental, not contingent.

Mach's arguments had a profound effect on Albert Einstein, who devised the general theory of relativity largely to abolish the idea of absolute motion, and indeed it was Einstein who, in 1918, coined the phrase "Mach's Principle." The basis of Einstein's general theory was his observation that the gravitational force the Earth exerts on you is canceled out in a freely falling elevator. When accelerating downward in an elevator whose cable has snapped, you feel weightless. By the same token, when accelerating upward in an elevator, you feel heavier than usual, as if the gravitational pull of the Earth has suddenly increased.

With "the happiest thought of his life," Einstein realized that within the elevator's confines, it is impossible to distinguish acceleration from gravity. To explain the origin of accelerations, then, he would need to create a theory of gravitation. Furthermore, because free fall abolishes gravity in an elevator, the origin of inertia cannot be found in the interaction with nearby bodies such as Earth. Inertia's origin must depend on the distant matter in the universe, as Mach had insisted.

Einstein hoped that, within the framework of general relativity, the distribution of matter of the universe would fully determine the inertia of material objects. Most modern discussions of Mach's Principle (when the topic comes up at all) center on whether general relativity succeeded in this goal. As simple as the question sounds, there is as yet no definitive answer.

While still formulating general relativity, Einstein calculated that the gravitational field of a shell of matter rotating around a gyroscope (picture a gyro inside a spinning, hollow Earth) would displace the gyro’s axis relative to the fixed stars. The gravitational field literally drags around the gyro’s “inertial compass.” In 1918, Austrian physicist Hans Thirring, with Einstein’s input, published a similar calculation based on the completed relativity theory. Josef Lense, an Austrian mathematician, later provided relevant astronomical observations. Inevitably, this concept of frame dragging has come to be known as the Lense-Thirring effect.

In the paltry gravitational field of the rotating Earth, the predicted amount of frame dragging is enough to displace the axis of an orbiting gyro by only 0.042 seconds of arc annually. That is roughly the angular size of a quarter held aloft by the Statue of Liberty in New York as viewed by William Penn atop Philadelphia’s city hall. Despite the challenge of measuring such a minuscule effect, frame dragging has been detected by the Laser Geometric Environmental Observation Survey (LAGEOS) and Gravity Probe B satellites, although the results were too uncertain to confirm the exact prediction of Einstein’s theory.

In 1963, New Zealander Roy Kerr, then at the University of Texas, discovered the general-relativistic description of rotating black holes. Soon physicists recognized that frame dragging can become far more pronounced around extreme astronomical bodies. Several teams have claimed to find observational evidence of frame dragging in the disks around supermassive black holes, although the results are indirect and imprecise.

The Cosmic Connection

There is no longer a question in any physicist's mind that general relativity predicts Machian effects on gyroscopes, and so far, the data seem to support Einstein's predictions. The question of how the distant reaches of the universe give marching orders to a gyroscope spinning on my desk is an altogether trickier issue.

The first triumph of general relativity was its exact prediction of the orbital precession of Mercury's perihelion: the small but puzzling 43 seconds of arc per century by which the point of the planet's closest approach to the Sun shifts with time, a movement that Newton's laws could not easily explain. Einstein described the gravitational field of the Sun in terms of curved space and showed that the curvature caused Mercury's perihelion to shift by precisely the right amount.

As physicist Erwin Schrödinger wrote, however, in a striking 1925 article on Mach's Principle, "…every naïve person has to ask: With respect to what, according to the theory, does the orbital ellipse perform this precession, which according to experience takes place with respect to the average system of the fixed stars?" In calculating the effects of curved space around the Sun, Einstein needed to assume that at large distances from the Sun, spacetime becomes flat—and absolute. In other words, he had to impose by fiat "boundary conditions" at infinity to complete his solution. General relativity, in and of itself, did not entirely determine the precession of Mercury's orbit.

Mathematician Kurt Gödel brought the point home in 1949 when he published a cosmological model designed to show that Mach and Einstein were incompatible. Gödel assumed the same uniform distribution of matter as Einstein did in his first cosmological model of 1917, but Gödel’s solution exhibited fundamentally different behavior. That discrepancy directly contradicted Einstein’s premise that the universe’s matter distribution should uniquely determine gyroscopic behavior.

The key difference was that Gödel’s universe rotated, meaning that distant galaxies rotate with respect to a gyroscope sitting on my desk, and that anyone, anywhere in the universe would observe the same behavior. (It does not mean that the universe is rotating around some central axis.) For true followers of Mach, a gyro should track the bulk matter of the cosmos, and so it should remain stationary with respect to distant galaxies. Since Gödel, researchers have found other rotating models of the universe, all of which similarly contradict Mach’s premise. Such models can be declared unphysical, however, because they flagrantly contradict observations of the real universe. Nevertheless, as theoretical solutions they demonstrate the difficulties that come with defining inertia purely in relation to other objects.

The litany of counterexamples eventually convinced Einstein to abandon Mach’s Principle. In 1990, however, Harry King, then at the University of Texas, proved that a closed universe—one that is destined to stop expanding and eventually recollapse—can exhibit no rotation. Any rotation of galaxies as in Gödel’s model is cancelled out by gravitational waves moving in the opposite direction. If Gödel’s result was a setback for Mach, then King’s result was a definite victory. Unfortunately, today’s cosmologists believe that the real universe is open—destined to expand forever—demonstrating again how difficult it is to connect a theoretical understanding of inertia to the actual cosmos.

More recently, Christoph Schmid of the Swiss Federal Institute of Technology claims to have vindicated both Einstein and Mach. Schmid has concluded that vorticity added to a realistic cosmological model would indeed drag gyroscope axes. But according to Schmid's calculations, the influence of matter diminishes exponentially beyond a critical radius, related to the distance that light has traveled since the Big Bang, and the exact shape of space at much larger distances becomes irrelevant. In this way, he bypasses the necessity to impose boundary conditions at infinity, the problem that bedeviled Einstein. The matter distribution of the universe in and of itself determines the behavior of gyroscopes. Schmid claims that general relativity then perfectly embodies Mach's Principle; on the other hand, some of his calculations are performed in a closed universe, which would seem to run afoul of King's proof.

In independent analyses, Cambridge University's Donald Lynden-Bell and his collaborators have accepted certain aspects of Schmid's results. Modern studies of the cosmic microwave background radiation, however, largely rule out any large-scale rotations in the universe. Many cosmologists believe that the universe went through an early inflationary period, in which the size of the universe increased exponentially. Such inflation would likely have damped out any rotation, leaving a still cosmos in which gyroscopes would naturally be at rest relative to distant matter, rendering Mach's Principle redundant—at least as far as rotating objects such as gyros are concerned. A non-rotating universe still does not necessarily explain the forces that push you back into the seat of a car when you accelerate along a straight line.

Does the law of inertia mean anything in an empty universe? Would you feel centrifugal forces? Mach would say no.

To most contemporary physicists, Mach's Principle is not merely redundant, it is forgotten entirely—as unknown to them as it may have been to the madcap graduate student flaunting his missile guidance system. Yet the mystery is never far away. To this day, we do not truly understand how the distant universe gives gyroscopes their marching orders.

The backwater of Mach's Principle holds many lessons. One is that the teaching of undergraduate physics has become divorced from the practice of physics. From arbitrary conventions that are presented as natural laws, to the insistence on precise answers to unrealistic problems, to the banishment of concepts such as centrifugal force, university physics has evolved to inhibit creativity rather than encourage it. How can one hold high the tenets of relativity—that physics can be performed in any reference frame—while simultaneously declaring that Newton's laws hold only in inertial frames? How can one begin to discuss Mach's Principle if one denies the very existence of centrifugal forces? Aye, centrifugal forces disappear in inertial frames; gravity disappears in free-falling elevators. Does that mean that gravity is a fictitious force?

Part of the difficulty in tackling Mach's Principle lies in its similarity to the utterances of the Delphic Oracle. Julian Barbour and Herbert Pfister, organizers of a 1993 conference on Mach's Principle in Tübingin, listed no fewer than 21 different interpretations. An exit poll at the conference's end revealed that only three attendees believed that general relativity perfectly embodied Mach's Principle, whereas 21 did not. Fourteen viewed it as "very Machian," and seven did not consider it Machian at all. An illustrious colleague recently remarked to me that he found Mach irrelevant for doing science: "Science for me was always a bunch of tools, not a branch of philosophy."

The greater obstacle is one of fashion. Today's cosmologists constantly wade into shallow philosophical waters if they align with tastes of the current scientific Pradas and Versaces. They worry about creating Big Bang models whose input parameters occur "naturally" rather than needing to be "fine-tuned" by hand. They consider the "cosmological constant problem"—why the "dark energy" driving the universe's expansion is some 125 orders of magnitude less than what you'd "expect"—to be the outstanding dilemma of their field. Physics or philosophy? Each year hundreds of papers are published on the string theory landscape and on the universe of universes—the multiverse. Each year dozens of conferences take place on particle physics or string theory. The only conference on Mach's Principle took place in 1993.

But replace the quaint-sounding words "Mach's Principle" with "Why does a gyroscope point in a direction fixed relative to distant quasars?" and one stands face to face with one of the most striking questions nature presents to us. It is more of a question than "How does the Higgs boson impart mass to other subatomic particles?" It is hardly less a question than "Why does time move forward when the basic laws of physics do not?" It is perhaps more fruitful than the vastly more popular question, "What lies behind quantum mechanics?” And Mach’s Principle outshines virtually all other riddles in one other category: It is pure romance.

We have a working theory of gravity, one that has been tested more precisely than any other theory ever devised. It accounts for the expansion of the universe; it describes the behavior of black holes; and it has successfully predicted the existence of gravitational waves. It should tell us why gyroscopes point at the stars.

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