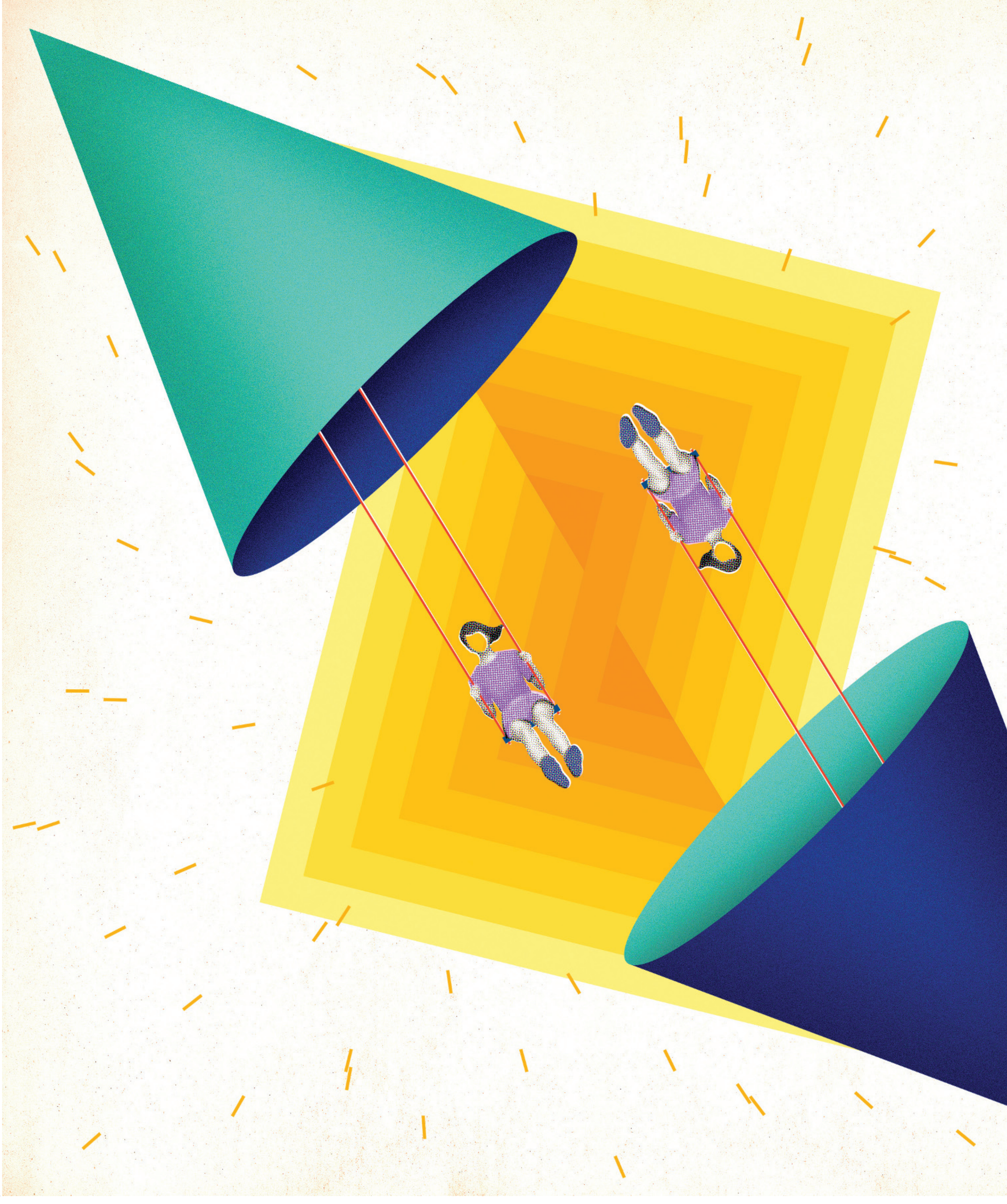

JIRAYU KOO

Our hopes of finding an ultimate theory depend on upsetting a balance that Einstein cherished, says **Stuart Clark**

Differently equal

COINCIDENCE is not generally something scientists have much truck with. If two things are genuinely unrelated, there is little further of interest to be said. If the coincidence keeps turning up, however, there must be some deeper underlying link. Then it is the job of science to tease out what it is and so explain why there was no coincidence in the first place.

That makes it rather odd that a large chunk of modern physics is precariously balanced on a whopping coincidence.

This coincidence is essential to the way we view and define mass. It is so fundamental to the world's workings that most of us encounter its consequences every day without giving them another thought. Yet it has vexed some of the best minds in physics for centuries. Galileo and Newton grappled with it, and ended up just accepting it, rather than understanding it. Einstein went one better: he declared it a principle of nature. He went on to use this "equivalence principle" as the fundament of his general theory of relativity, still our best stab at explaining the mysterious force of gravity.

But there is a problem. If we want to find some bigger, better theory that can unify gravity with the other forces that dictate the world's workings, the equivalence principle cannot stay. We must either unmask this coincidence – or radically rethink how physics can progress from here.

There are several versions of the equivalence principle, but all boil down to one idea: that the effects of gravitational fields are indistinguishable from the effects of accelerated motion. A thought experiment of Einstein's expresses it best. Imagine a person standing inside an elevator on Earth. What keeps their feet firmly planted on the floor? The inexorable pull of gravity downwards, of course. Now imagine the same person in the same lift, but in empty space far from any gravitating object. In this case a rocket just so happens to be pushing the lift up in empty space with the same acceleration that Earth's gravity produces. The passenger will remain squarely on the lift floor in exactly the same way (see "An enigmatic equivalence", page 34).

How so, when there is no gravity involved? In this case, it is the person's inertia that is preventing them floating upwards. Inertia is the natural resistance of any body to acceleration – the same effect that pushes you back into your car seat when the driver puts their foot down.

The two elevator situations have a common property, mass. But the two masses come from very different places. One, gravitational mass, is something that responds to the pull of gravity, tending to accelerate a body in a gravitational field. The other, inertial mass, is the property of a body that opposes any acceleration.

Another way of stating the equivalence principle is to say that these two masses are always numerically exactly the same. The consequences of this coincidence are profound. If the two masses weren't the same, objects of different masses could fall to Earth at different rates, rather than all accelerating in the same way in a gravitational field. This "universality of freefall" was apocryphally first tested by Galileo dropping a bag of feathers and a bag of lead shot from the Leaning Tower of Pisa. In fact, the equality of gravitational and inertial mass dictates all

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gravitational motion throughout the universe. If gravitational mass responded just a little bit more to gravity than inertial mass does to acceleration, for example, then planets would orbit their stars and stars orbit their galaxies just a little bit faster than they do.

Yet there is no obvious reason why this correspondence should be so. It was only by assuming it was that Einstein fully developed the strange contortions and contractions of time and space he had first introduced in his special theory of relativity in 1905. What if a massive object such as a planet, Einstein wondered, squeezes the surrounding space into successively more compact volumes the closer you get to it? As something moved towards the planet's surface, it would then take less and less time to cross these compacted spaces: it would appear to accelerate.

The odd force

By 1916, this thought had guided Einstein to his general theory of relativity. What looks like gravity is just uniform motion through a progressively compacted space. And if there is no gravity, gravitational mass is fictitious too. The only mass at work in the universe is the one that gives a body its inertia. The coincidence behind equivalence disappears.

General relativity is, as far as we have tested it, peerlessly accurate, predicting the positions of celestial bodies and guiding our satellites with minute precision. Yet there is something odd about it that physicists don't like. All the other forces of nature are transmitted between bodies by physical, if ethereal, quantum particles. The electromagnetic force, for example, is transmitted between bodies with electrical charge by the exchange of the massless particles called photons. Outwardly, gravity works in exactly the same way. It looks like a duck, swims like a duck – but it can't quite be made to quack like a duck.

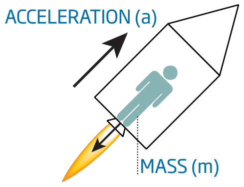
Attempts to make gravity quack with a quantum voice are the guiding thought behind string theory and other projects to construct all-embracing "theories of everything". But if gravity is to be reborn as a real force, it needs something to latch on to, just as electromagnetism latches on to electric charge. It needs a gravitational mass that is separate and distinct from inertial mass.

That means progress towards a theory of everything has an essential first step: slaying Einstein's holy cow. "Any theory of quantum gravity must violate the equivalence principle at some level," says Ben Gripaios, a theoretical physicist at the University of Cambridge.

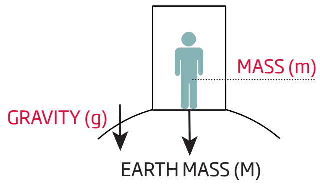
An enigmatic equivalence

Einstein's equivalence principle states that the physics of acceleration and gravity work in exactly the same way. But there's no reason why that should be the case

Accelerate a rocket in gravity-free space and a body's inertial mass will resist the motion



The mutual attraction between gravitational masses is what keeps our feet on the ground



In all situations

inertial mass $\equiv$ gravitational mass

acceleration $\equiv$ gravity

It's only by assuming the equivalence principle is true that we can explain that bodies at the same distance from Earth fall to the ground at the same rate

Newton's 2nd law of motion

Newton's gravitational law

$$\textbf{force} = \overset{\text{mass}}{m} \times \overset{\text{acceleration}}{a} = \overset{\text{mass}}{m} \times \frac{\overset{\text{Gravitational constant}}{G}\ \overset{\text{Mass of Earth}}{M}}{\underset{\text{Distance between body and centre of the Earth}}{r^2}}$$

If $m = m$

then $$\underbrace{a = \frac{G\ M}{r^2}} = g$$

At a distance (r) from Earth's centre, the acceleration due to gravity (g) is ALWAYS THE SAME

How? One tried and tested method is to attempt to prove that the two masses aren't actually equivalent at all – just very, very close. Even the slightest sliver of a difference would mean that general relativity is built on an approximation and that a deeper, more precise theory must exist. "If someone finds a difference then we have made a major breakthrough," says Claus Lämmerzahl of the University of Bremen in Germany.

A way to do this is to continue on in the spirit of Galileo's Leaning Tower experiments, testing the universality of free fall and other consequences of the equivalence principle in the hope of teasing out some tiny anomaly – so far with little success (see "Drop the subject", page 35). Meanwhile, theorists are picking at a different thread. They point out that whether or not Einstein was right about there being no gravity, just inertia, no one has yet come up with a convincing explanation of inertia. "We do not yet know how to define it," says Gripaios. "We know it must be related closely to mass, but until we can define it precisely and know how to measure it, there can be no theory for it."

> "Gravity looks like a duck and swims like a duck – but it can't quite be made to quack like a duck"

One thing's for sure: it doesn't all come from the Higgs field, feted as the giver of mass. Evidence for the existence of this field and its associated particle was presented by physicists sifting through the debris of particle collisions at the Large Hadron Collider at CERN near Geneva, Switzerland, last year. But while the

Higgs field is thought to give fundamental particles such as electrons and quarks their mass, when quarks combine into the heavier particles, protons and neutrons, that make up the bulk of normal matter, the resulting mass is roughly a thousand times the summed mass of the constituent quarks. This extra mass comes not from the Higgs mechanism, but from the energy needed to keep the quarks together. Somehow, these two effects must combine and latch on to something else to create the property of a body's resistance to acceleration. "There is no way the Higgs alone can be some sort of mysterious ingredient that gives inertia," says Gripaios.

What then? One suggestion has its origins in work by Stephen Hawking in the 1970s. Ironically, it was motivated back then by a strict application of the equivalence principle. Hawking was investigating the properties of black holes, the unimaginably dense gravitating bodies whose existence is a central prediction of general relativity. He suggested that a black hole should be an apparent source of radiation, because pairs of quantum particles that constantly pop up in space would become separated close to a black hole, with one being sucked in and the other spat out. That led the Canadian physicist William Unruh and others to suggest that, if gravitation and acceleration really are one and the same thing, similar emissions should be a feature of any body accelerating in a vacuum.

Nothing doing

Like Hawking's radiation, Unruh's has never been unambiguously detected. The accelerations necessary to achieve a measurable effect in a lab are generally too high, although some argue the effect has been seen with electrons accelerated in the high magnetic fields of particle accelerators.

A decade or so on from Unruh's original work, astrophysicist Bernard Haisch of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, and electrical engineer Alfonso Rueda of California State University in Long Beach were playing with a similar idea when they realised the vacuum's interaction with an accelerating body would not just occur on its surface, but permeate its entire volume. That could produce a force that acts in the opposite direction to the body's movement. They originally likened it to the way in which charged particles moving through a magnetic field experience a force – the Lorentz force – that affects their motion. In this case there were electromagnetic

DROP THE SUBJECT


ZARM

Looming 146 metres over the north German plain like a great white rocket poised for take-off, it's hard to ignore the University of Bremen's "drop tower" (picture, right). Inaugurated in 1990 as part of the Center of Applied Space Technology and Microgravity (ZARM), it provides up to 9.3 seconds of free fall in which to conduct experiments. So far tests of rubidium and potassium atoms in free fall have provided no deviation from the behaviour predicted by the equivalence principle (see main story). The atoms have been found to fall at the same rate to accuracies of 11 decimal places.

At the University of Washington in Seattle, meanwhile, Eric Adelberger and his "Eöt-Wash" team use a high-tech set of scales known as a torsion balance to compare the motions of standard masses made of different elements, including copper, beryllium, aluminium and silicon. They hold the record for test accuracy, with no violations of the equivalence principle to 13 decimal places.

At some point, however, these earthbound experiments are going to hit a brick wall. "It is getting harder to make the instruments better," says Adelberger. Working somewhere where gravity is a lot smaller would make any deviations from equivalence a lot easier to spot. The French-led MICROSCOPE mission due to launch in 2016 will do just that, testing the motions of masses of platinum and iridium in the microgravity conditions of space. "MICROSCOPE will achieve an accuracy 100 times better than a laboratory on Earth," says Claus Lämmerzahl of ZARM.

His organisation is testing the satellite's accelerometers in their drop tower, and also developing the software needed to analyse the satellite's final results. An even more sensitive mission, the Space-Time Explorer and Quantum Equivalence Principle Space Test, is currently being evaluated by the European Space Agency, with a decision on funding due by the end of this year.


ZARM

If objects fall at different rates under gravity, the equivalence principle is broken

JIRAYU KOO

DARK INERTIA

In the 1930s, we noticed that galaxies spinning around other galaxies were not moving as Newton's and Einstein's laws of gravity dictated. A few decades later, something similar was observed of the rotation of individual spiral galaxies. It was almost as if some invisible matter was whirling the matter we could see around faster.

That idea has now become mainstream: standard cosmology textbooks will tell you that "dark matter" outweighs normal matter by a factor of 5 to 1. Yet despite particle physicists supplying an almost endless list of hypothetical particles that might fit the bill, to date none has been definitively detected.

An alternative first championed in the 1980s by Mordehai Milgrom, a physicist then at Princeton University, is that gravity must somehow be modified at a galaxy's edges. This could be explained if there was a drop in inertial mass without a drop in gravitational mass for stars experiencing the ultra-low accelerations found at the outskirts of galaxies. This would naturally make them move faster. If vacuum interactions can really bring this about (see main story), they could be just the ticket to mimic dark matter.

interactions with the quantum vacuum. "It appears to be exactly what you need for inertia," says Haisch.

Anomalous accelerations

Mike McCulloch of the University of Plymouth, UK, thinks such interactions are also just what you need to break the equivalence principle. One prediction made of Unruh radiation is that, like the rays emitted from a hot body, it comes in a spectrum of many different wavelengths. For very small accelerations, the temperature of the radiation that a body "sees" from the vacuum is low, and dominated by very long wavelengths. Make the acceleration very small indeed, and some of these wavelengths become longer than the size of the observable universe, effectively cutting them off.

In this case, according to calculations McCulloch did in 2007, originally to explain the seemingly anomalous accelerations of the Pioneer spacecraft as they crossed the solar system, the total amount of Unruh radiation experienced by a body would drop, and it would feel less of an opposing force. Its inertia would thus fall, making it easier to move than Newton's standard laws of motion dictate – and cutting the connection with gravitational mass.

The problem with this idea is testing it. In the high-gravity environment of Earth, accelerations small enough for the effect to be observed would not be easy to manufacture. But its effects might well be seen in a low-gravity environment such as that found at the edge of a galaxy. Indeed, looking at the anomalous motions of most spiral galaxies, McCulloch suggests this mechanism could also explain another enduring cosmic mystery – that of dark matter (see "Dark inertia", above).

It's fair to say such ideas have not set the world alight. When Haisch and Rueda came up with their mechanism, NASA was sufficiently impressed to fund further study and the duo also attracted some $2 million in private investment. But the lack of testable predictions of how the effect might manifest itself led the money and interest to dry up.

Nevertheless, a traditionalist such as Lämmerzahl thinks we should not dismiss the idea out of hand. "Even though I follow more the ideas of string theory, these ideas of vacuum interactions are not nonsense," he says. "We need to look at them seriously and decide whether they give us new ways to test the equivalence principle."

One proposal to do that was made in 2010 by a trio of Brazilian astronomers led by Vitorio De Lorenci of the Federal University of Itajubá. They suggested using a spinning disc to cancel out the accelerations produced by Earth's rotation and its movement through space. At minuscule accelerations, the disc's inertia would drop, meaning it would spin faster than expected from Newton's laws. Despite a relatively modest cost, however, no money has yet been forthcoming to fund the experiment.

And so the deadlock remains until someone delivers either an experiment that exposes the equivalence principle as a sham, or a theoretical idea that shows why it must be just so. But if in the end gravitational mass is indeed just inertial mass in another guise – whatever inertial mass is – then it will be the quantum theories of gravity, including string theories, that will find themselves laid upon the sacrificial altar. Paths to a theory of everything will become even more winding. If gravity is not a force, but truly an illusion that springs from the warping of space, as described by general relativity, we will have to look more closely to understand at a basic level what makes that warping come about.

Just a coincidence? This is one that science is not finding so easy to dismiss. ■

Stuart Clark is a consultant to *New Scientist* and the author of *The Sky's Dark Labyrinth* trilogy (Polygon)