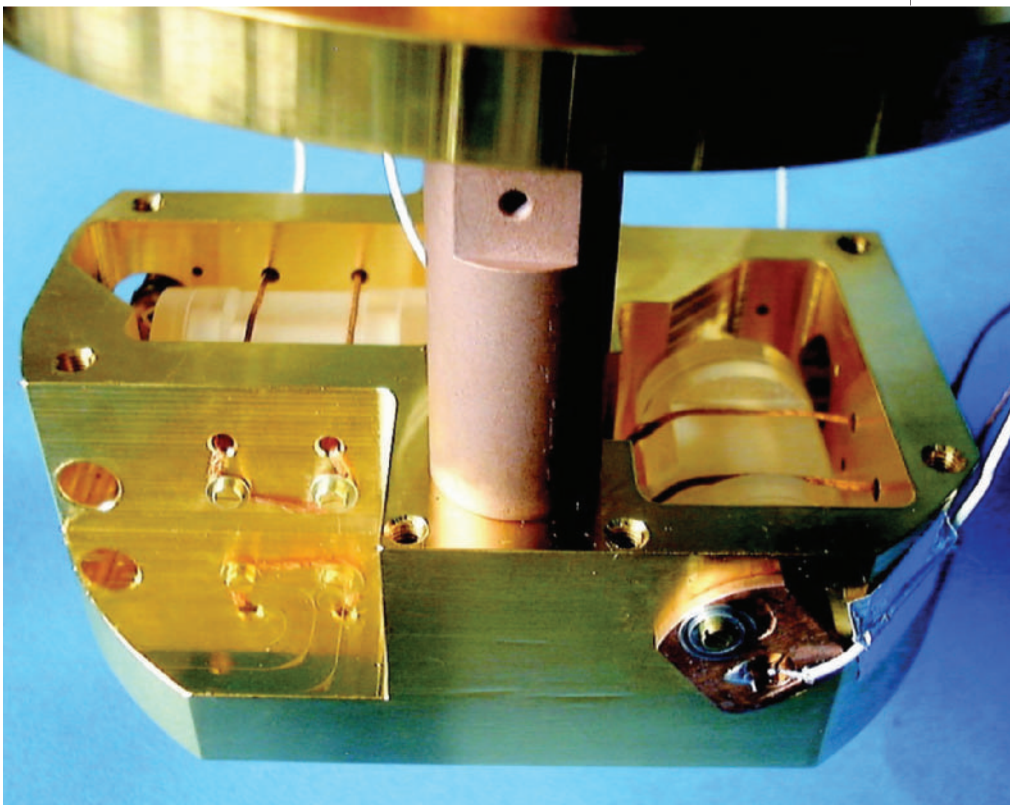
Back to the future

From reruns of a nineteenth-century experiment performed with breathtaking precision, we may gain our first glimpses of the physics that lies beyond Einstein's theories of relativity. Philip Ball reports.



Light box: Michelson and Morley's original experimental set-up (right) and its modern-day equivalent (above) — optical resonators that measure the speed of light more accurately.

A negative result is not always bad news. In 1887, the physicists Albert Michelson and Edward Morley[1] failed to detect the influence of the mysterious 'ether' — the medium through which light waves were thought to travel. As they surveyed their apparatus, held in a basement in Cleveland, Ohio, they must have been disappointed. Yet just a few years later, Albert Einstein, inspired in part by Michelson and Morley's experiment, announced his revolutionary theories of relativity[2] and completely reinvented our notion of space, time and gravity.

Today, experimentalists in France and Germany are rerunning Michelson and Morley's experiment with unprecedented precision[3,4]. But this time they are not looking for the ether. By pushing this test of the constancy of the speed of light to its limits, they hope to find signs of new physics beyond Einstein's equations. If they do, they may be the first to cross the experimental threshold into an exotic new world of 'quantum gravity'. Even a negative result — essentially one that agrees with Einstein's theories — might, if it is sufficiently precise, be able to rule out or modify certain ideas about quantum gravity.

Elsewhere, the hunt for physics beyond Einstein's theories is looking out at the cosmos. A team at the University of Maryland recently put relativity to the test by studying radiation emitted by an exploding star 6,000 light years away[5]. These violent events act as natural particle accelerators, allowing scientists to probe energies far greater than any available from instruments on Earth. As the energy increases, the prospects of seeing a flaw in relativity become ever greater.

Universal theory

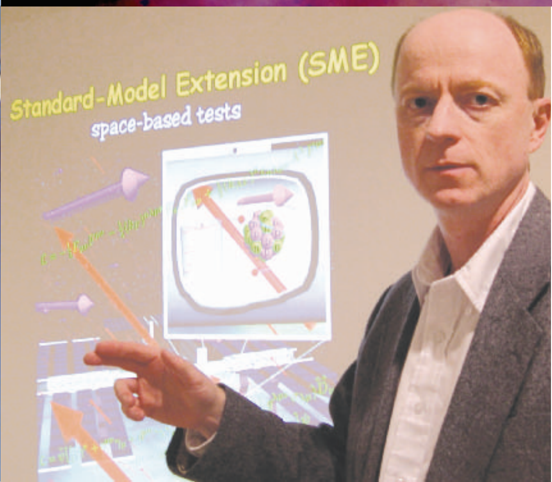
The possibility that experimentalists can tell which of the theorists' ideas are right or wrong is an exciting development, explains David Mattingly, a member of the Maryland team and now at the University of California, Davis. "Researchers studying quantum gravity have long lamented the 'desert' of experimental input. Now observation is catching up," he says.

This matters because we expect the laws of nature to be seamless. Yet for the past century physicists have had to get by with two incompatible theories about the way in which the Universe works. They have one set of laws for gravity, courtesy of Einstein's general theory of relativity, and another set — quantum theory — for the other three fundamental forces of nature: electromagnetism and the strong and weak nuclear forces. This works surprisingly well most of the time, but in more extreme environments, such as inside black holes or during the early moments of the Big Bang, the two theories start coming into conflict. It would be absurd if they were not ultimately part of the same universal framework. This is why theorists are struggling to develop a quantum theory of gravity, in which the gravitational force is carried by discrete particles.

What is so special about the Michelson–Morley experiment that it could turn our notions of the Universe upside-down for a second time? Before relativity, light waves were thought to travel through the ether, a medium assumed to pervade the Universe — just as sound waves travel through air. Michelson and Morley set out to detect the ether by recording the velocity of beams of light travelling in different directions. They expected to see different speeds for each beam, caused by the motion of Earth through the ether. To their surprise, they saw nothing of the sort — the speed of light remained constant in all directions.

Einstein showed why this was so. A positive result would have been in conflict with one of the cornerstones of relativity, an idea called Lorentz invariance. Named after the Dutch physicist Hendrik Lorentz, who derived it in 1904, this essentially says that the laws of physics don't change when we

NASA/SPL



The Crab nebula (above) is used to test relativity, while theorist Alan Kostelecky (left) considers light from galaxies much farther away.

switch between different reference frames, such as those moving at different speeds[6]. Lorentz also tried to explain Michelson and Morley's experiment with his idea. But instead of concluding that the ether didn't exist, he argued that the ether could define a 'universal' reference frame against which all other motions were defined.

Light standard

Einstein wasted no time in getting rid of the ether, but he kept Lorentz invariance as a fundamental feature of relativity. In essence, Einstein said there is no absolute reference frame; rather, it is the speed of light that provides an unvarying reference against which all other motions must be measured. Practically speaking, Lorentz invariance means that the result of an experiment doesn't depend on the speed or orientation of the laboratory. Einstein took care to include Lorentz invariance in relativity because he needed the laws of electromagnetism, which dictate the properties of light, to hold true everywhere and in all reference frames.

That's why the Michelson–Morley experiment remains relevant today: it is a way of investigating to what level of accuracy the fundamental ideas of relativity hold true, without necessarily having to know anything about the new physics that lies beyond.

Some theories of quantum gravity predict that Lorentz invariance will fail over very small distances or at very high energies. So physicists are looking for signs of this failure, or 'violation', in their experiments. "The observation of Lorentz violation would be a sensitive signal for unconventional physics," says Alan Kostelecky, a theoretical physicist at Indiana University in Bloomington.

This feature of relativity is now being tested in laboratories in France and Germany using high-tech versions of the Michelson–Morley experiment. Both groups are looking for tiny changes in the time it takes a light or microwave signal to travel through crystalline structures called resonators. They use resonators made of sapphire and cooled to liquid-helium temperatures, allowing high-precision measurements.

These experiments are fundamentally similar to Michelson and Morley's in that they measure the motion of light in different reference frames. This is important because the measurement of motion changes depending on your frame of reference. For example, if a ball is thrown along a train carriage moving at 100 kilometres per hour, a passenger in the carriage sees the ball travelling at, say, 20 km h^{-1} whereas an observer on the platform would see the ball travelling at 120 km h^{-1}.

The French team at the Paris Observatory, headed by Peter Wolf, and collaborators in Australia have measured how the motion of Earth, as it spins on its axis and orbits the Sun, affects the travel time of a light beam circulating around a ring-shaped resonator[3]. This provides the researchers with two tests of Lorentz invariance that involve reference frames pointing in different directions — as in the Michelson–Morley experiment — or moving at different speeds.

So far, Einstein's equations pass both tests with flying colours — Wolf's team has detected no violation of Lorentz invariance, even though its experiment is 30 times more precise than previous tests. More recently, the team has made experimental improvements that further enhance the accuracy by a factor of two[7]. "That is about the best we can do," says Wolf. "For further improvements, you'd need a different set-up."

The German researchers, headed by Stephan Schiller at the Heinrich-Heine-University of Düsseldorf and Achim Peters at the Humboldt University of Berlin, have been using two optical resonators in their latest experiments, comparing them against each other[4]. This, they say, doubles the signal amplitude and helps to eliminate some sources of systematic error. The researchers found an upper limit for Lorentz invariance very close to that deduced by Wolf's team.

Into space

Schiller hopes that these limits will be made 1,000 times more accurate by an experiment that repeats the resonator measurements in space, on board a small satellite called OPTIS. In space, the resonators experience far less environmental vibration than on Earth, making the measurements more accurate. Schiller and Peters' team are collaborating with space researchers at the University of Bremen in Germany to develop the OPTIS project, which would also carry ultra-stable atomic clocks to provide further tests of relativity.

OPTIS has received funding from the German Space Agency, and Schiller hopes for support from the European Space Agency (ESA). "The central technology issues could be worked out in about four years," he says — but the project hangs in the balance, pending the nod from ESA. Other space-based searches for Lorentz violation are planned for the International Space Station. These include both Michelson–Morley-type experiments and ones involving atomic clocks. The earliest launch date for any of these is 2005.

What might a theory of quantum gravity look like? The electromagnetic force and the strong and weak nuclear forces are known to be transmitted by fundamental 'quantum' particles, the most familiar being the photon, for electromagnetic interactions. Physicists feel sure that the fourth fundamental force, gravity, must also have an associated quantum particle, the graviton.

But no one has yet found a way to introduce this particle in a way that fits with the picture of gravity painted by general relativity. Relativity assumes the fabric of space-time to be smooth and continuous, whereas quantum theory wants to make it grainy. That graininess is predicted to reveal itself only at an unimaginably small scale of 10^{-35} m — called the Planck distance. This is some 20 orders of magnitude smaller than an atomic nucleus. "The Planck scale appears in almost all the different approaches to quantum gravity," says Mattingly.

The trouble is that grainy space-time doesn't follow the rules of relativity. In particular, many popular theories of quantum gravity suggest that, at the Planck scale, Lorentz invariance will break down. Some theories demand Lorentz violation; others seem merely to permit it. For example, the two leading candidates — string theory and loop quantum gravity — both permit Lorentz violation to varying degrees. String theory attempts to treat gravity and the other fundamental forces within the same mathematical framework, but it lacks concrete experimental predictions. Loop quantum gravity rewrites the principles of relativity in a form that is closer to quantum theory, to generate grainy space-time at the Planck scale.

Glowing report: Peter Wolf (second from right) and his team are tracking the effects of Earth's motion on the speed of light.

High energy

These separate theories have been developed by different communities of devoted researchers over the past two decades. They have evolved into many varieties and flavours, but in the absence of any experimental data, no one can say which approach — if any — will succeed. A variation of string theory in which there are multiple membrane-like universes, or 'brane worlds', suggests that weak gravitons, leaking into our world from another dimension, would violate Lorentz invariance[8]. Other exotic ideas about the behaviour and structure of space-time at the Planck scale — known as noncommutative geometry and spin-foam models — also permit Lorentz violation.

Another way to catch a glimpse of the physics beyond relativity is to use the Universe itself to probe distance and energy scales we cannot hope to create on Earth. The Planck distance can be assigned an equivalent Planck energy, which physicists calculate to be about 10^{28} electron volts (eV). This is 16 orders of magnitude greater than the energies that will be available to the next generation of Earth-bound particle accelerators — such as the one under construction at CERN, the European laboratory for particle physics, near Geneva.

Luckily, astrophysical sources can do better. Supernovae — old stars that have collapsed on themselves and then exploded — often turn into ultra-dense stars that throw out extremely energetic particles. Mattingly and his collaborators Ted Jacobson and Stefano Liberati have focused their sights on the Crab nebula, the expanding gaseous remnant of a supernova, where electrons reach energies of about 1.5×10^{15} eV.

At these energies the electrons are moving at almost the speed of light, and they emit high-energy X-rays as they get deflected by magnetic fields in the nebula — exactly as if they were in a particle accelerator. By analysing these X-rays, Mattingly and colleagues can see how fast the electrons are whizzing around. Lorentz violation would restrict the electron's top speed, preventing it from reaching the speed of light. But the Maryland team hasn't yet found any evidence for Lorentz violation, even though their observations allow them to extrapolate to energies seven orders of magnitude higher than the Planck energy.

Studies like this exploit not only the very high energies of astrophysical sources but also the huge distances over which their light must travel to reach us. This allows incredibly tiny effects of Lorentz violation to be amplified into detectable ones. The idea was used by Kostelecky and his graduate student Matthew Mewes in 2001 to place the tightest bounds anyone has so far put on Lorentz violation, by looking for rotation of polarized light from very distant galaxies[9]. If Lorentz invariance is violated, the light would rotate as it travels through space — although this would be detectable only for light that has travelled over very long distances.

Although neither lab-based experiments nor astrophysical observations have directly detected Lorentz violation yet, their 'negative' results can already be used to probe some of the candidate theories for quantum gravity. "We are unable to rule out a whole theory," says Mattingly, "but we can still rule out certain variants." Calculations from loop quantum gravity, for instance, already hint at contradictions with the observations. But that doesn't necessarily mean that every version of loop quantum gravity is wrong; the theory is still not well enough understood to place that much faith in the calculations. The same is true for other ideas, such as spin-foam and brane-world models: they seem to predict too much Lorentz violation, but we can't be sure.

Mattingly says that theorists are starting to revise their models in response to the new observations. For example, a recent paper[10] already claims to have restored Lorentz invariance to quantum loop gravity. "Until recently, even this type of observational feedback to a theory of quantum gravity would have been impossible," Mattingly says. "Theorists never used to have to revise their theories to be compatible with experiment, because there weren't any experiments." ■

Philip Ball is a consultant editor of *Nature*.

1. Michelson, A. A. & Morley, E. W. *Am. J. Sci.* **34,** 333 (1887).
2. Einstein, A. *Ann. Phys.* **17,** 891 (1905).
3. Wolf, P. *et al. Phys. Rev. Lett.* **90,** 060402 (2003).
4. Müller, H., Herrmann, S., Braxmaier, C., Schiller, S. & Peters, A. *Phys. Rev. Lett.* **91,** 020401 (2003).
5. Jacobson, T., Liberati, S. & Mattingly, D. *Nature* **424,** 1019–1021 (2003).
6. Lorentz, H. A. *Proc Acad. Sci. Amsterdam* **6,** 809–831 (1904).
7. Wolf, P. *et al.* preprint at <www.arxiv.org/abs/gr-qc/0306047> (2003).
8. Burgess, C. P., Núnez, C., Quevedo, F., Zavala, I. & Tasinato, G. J. *High-Energy Phys.* **8,** 056 (2003).
9. Kostelecky, V. A. & Mewes, M. *Phys. Rev. Lett.* **87,** 251304 (2001).
10. Kozameh, C. N. & Parisi, M. F. preprint at <www.arxiv.org/abs/gr-qc/0310014> (2003).