FEEL THE FORCE

When two objects separated by a vacuum are barely a whisker apart, a strange attraction comes into play. **Philip Ball** meets the physicists who are trying to make something out of nothing.

D. PARKER/SPL

"Nothing can come of nothing," wrote Shakespeare, but Harvard physicist Federico Capasso aims to prove him wrong. Because of the fluctuating nature of the sub-microscopic quantum world, 'nothing' — a vacuum — can generate an attractive force between two objects that are very close to each other. This Casimir force, named after its discoverer, Dutch physicist Hendrik Casimir, has long been regarded as a scientific curiosity. But Capasso believes that it can be tamed and modified in ways that could benefit technology at the microscopic scale. Thanks largely to his vision, the field of Casimir engineering is beginning to take shape.

The Casimir force is so weak it is almost undetectable. As a result, much of the work on this ghostly interaction has been concerned with simply detecting and characterizing it. Hardly anyone has thought about whether it could be put to good use.

But Capasso believes that there is "a whole zoo of interesting stuff" that can be done with the force. He wants to use it to make new microscopic devices, such as motion and position sensors[1]. "I love to think of myself as a designer," says Capasso, "and here the question is, can we design quantum fluctuations?"

These fluctuations lie at the heart of the attractive force. All materials — and vacuums too — are pervaded by fluctuating electromagnetic fields. These fluctuations in two closely separated surfaces can get in step, leading to an electrical attraction between them. That gives rise to the familiar van der Waals force, famous for helping geckos to climb glass walls: an illustration that this fundamentally quantum-mechanical effect has observable everyday consequences.

But experiments in the 1940s showed that this attractive force falls off more rapidly than expected at separations of more than 10 nanometres or so (see 'Into the gap'). In 1948, Casimir explained why. The fluctuations of one surface are 'communicated' to the other by fluctuations of the electromagnetic field in the vacuum in between. But as the gap gets bigger, it takes longer for this 'signal' to cross, and so there is a time delay: the surface fluctuations get out of step, and the force therefore gets weaker. This weaker attraction is now generally called the Casimir force, although in a sense it is simply a modification of the van der Waals force.

It took several more decades for this elusive effect to be measured directly. The Casimir force falls off rapidly with increasing separation and is tiny beyond a few tens of nanometres. But its strength increases with the area of the interacting surfaces, so it becomes detectable if the surfaces are big enough. This does, however, mean holding two parallel surfaces only a microscopic distance apart, which is technically demanding, especially given that such surfaces are generally rather rough and so may not have a well-defined separation.

That's why the Casimir force wasn't detected unambiguously with high precision until 1997, when Steve Lamoreaux, then at the University of Washington in Seattle, measured the interaction between a gold-plated hemisphere and a gold plate attached to a torsion pendulum: a horizontal bar suspended by a wire. As the objects were brought to within a few micrometres of each other, the force caused the pendulum to twist[2].

Weak and feeble?

It is difficult to imagine that a force so weak that it is hard to measure at all is likely to be significant in applied science, either as a problem or an opportunity. But the small scales on which engineering is now being conducted have revitalized interest in the Casimir force. Mechanical devices such as vibration sensors and switches are now routinely made with parts that are just a few micrometres big.

These microelectromechanical systems (MEMS) are just the right size for the Casimir force to exert itself: they have surface areas big enough, yet gaps small enough, for the force to draw components together and perhaps lock them tight — an effect called stiction. Such permanent adhesion is a common cause of malfunction in MEMS devices, and in 1998 Jordan Maclay and his co-workers at the University of Illinois in Chicago suggested that the Casimir force might be responsible for it[3].

"This is a phenomenon that most researchers try to avoid rather than study."
— Ho Bun Chan

This makes sense to MEMS researchers such as Ho Bun Chan at the University of Florida in

Gainesville. "The components in MEMS are designed to be very close to each other," says Chan, who has worked on Casimir forces in these systems. "Under the right circumstances, the Casimir force can become significant and affect the operation of the device. It can initiate the pull-in of components that eventually leads to stiction."

He admits that so far there have been no reports of this, but adds that most researchers in this field have probably seen it unknowingly. One attempt to look for it explicitly was made in 2001, when physicists Eyal Buks and Michael Roukes at the California Institute of Technology in Pasadena investigated stiction between a nanoscale gold beam, fixed at both ends, and an adjacent gold electrode[4].

Sticking point

They brought the two metal surfaces into contact using the capillary forces of a droplet of water placed between them, and found that the beam stayed stuck after the water had evaporated. The interaction was a combination of the van der Waals force where the surfaces were in contact, and the Casimir force where there was a gap.

Chan notes that in experiments he has done, the smallest possible separation between two MEMS surfaces is about 60 nanometres or more. "If we go beyond this distance, we find that the plates jump into contact, presumably due to the Casimir force," he says. "However, this is a phenomenon that most researchers try to avoid rather than study."

Although more work is needed to find out whether the Casimir force triggers stiction in MEMS, Capasso and his co-workers have verified that it can be detected in such devices. They think that the force could in fact be used to start mechanical motion. "As you load more and more MEMS devices on to a chip, at some point you have to contend with this effect," Capasso says. "Either you must avoid it or you must use it."

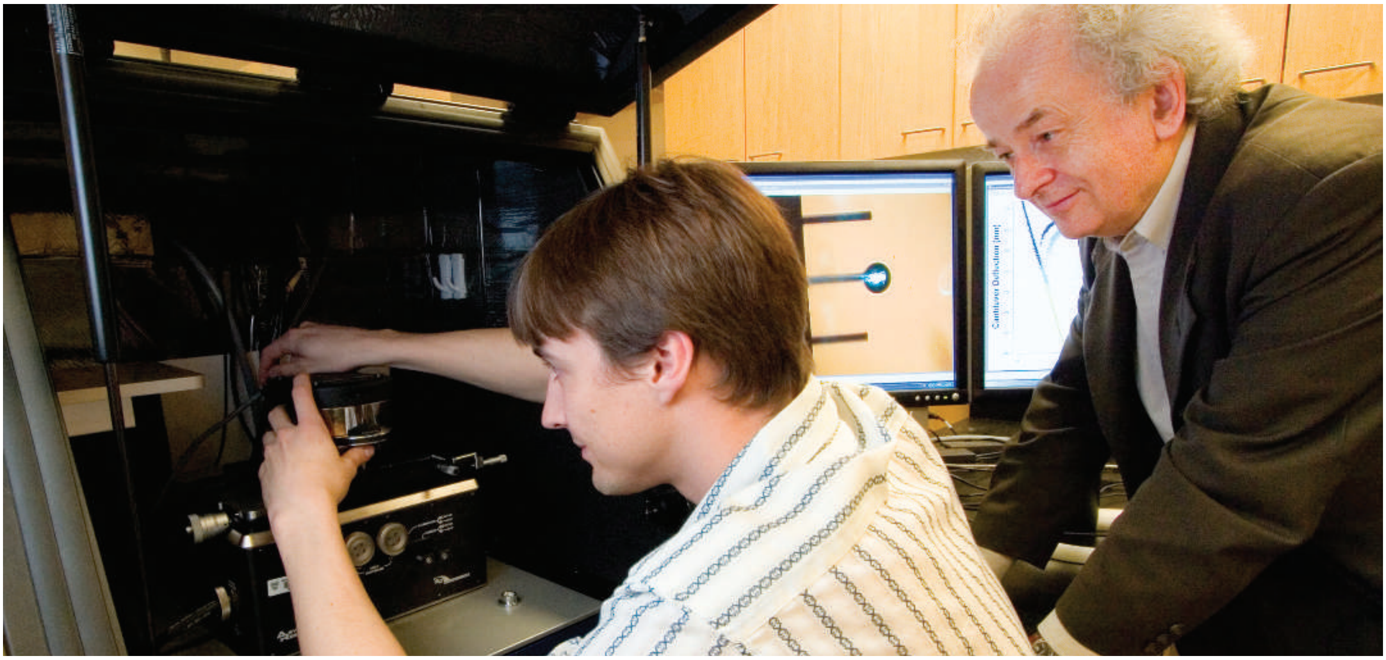
Capasso's fascination with the Casimir force began during the 1990s, while he was working at Bell Labs in Murray Hill, New Jersey. In 2001, he and his Bell colleagues devised a MEMS device that enabled them to probe the Casimir force in an accurate and controlled way[5]. The device measured the attraction between a gold-coated sphere and the surface of a see-saw made from two square silicon plates that were coated in gold (see picture, overleaf).

"As you load more and more devices on to a chip, at some point you have to contend with the Casimir effect."
— Federico Capasso

The Casimir force between the plates and sphere drew one side of the see-saw upwards. The tilt increased sharply at separations of less than about 150 nm, but the researchers could detect it for separations of at least 300 nm. The amount the plate tilted matched very closely that predicted from Casimir's theory. In principle, the researchers can exert precise control over the Casimir interaction because electrodes beneath the see-saw (used to measure its movement) offer the option of tilting the plate using electrostatic interactions. Because this would entail balancing electrostatic forces, elastic forces in the see-saw and the Casimir interaction, the researchers can control the interaction in ways that might be exploited in future MEMS devices.

Further opportunities for engineering the Casimir force arise because the interaction depends on the composition of the interacting materials. There have even been predictions of a repulsive Casimir force. "Between two flat plates with vacuum in between, the Casimir force is always attractive," says physicist Astrid Lambrecht of the Kastler Brossel Laboratory in Paris. But with another medium in between the plates, such as certain types of liquid, she says, you can have repulsion.

No one has yet seen a repulsive Casimir force experimentally. It requires picking materials that have the appropriate electromagnetic responses at different wavelengths. But earlier this year, Capasso reported experiments on two gold surfaces immersed in ethanol[6]. The force between them remained attractive, but it was only half as strong as that when the surfaces were separated by air. "This is a stepping-stone experiment," he says. "By replacing one of the surfaces with silica or Teflon, we might expect to see a repulsive force. But it is very difficult stuff — you have to be paranoid about possible sources of error." Capasso believes that engineering a repulsive force could be used



E. GRINNEL/HARVARD UNIV.

Federico Capasso (right) and Jeremy Munday set up an experiment to investigate the ghostly interactions caused by the Casimir force.

Into the gap

In the 1940s, Theo Overbeek and Evert Verwey at the Philips Research Laboratories in Eindhoven, the Netherlands, made accurate measurements of the attractive van der Waals force predicted to exist between all atoms, molecules and small particles owing to random fluctuations in their clouds of electrons. This force was thought to be fully explained by the 1930 quantum-mechanical theory of Fritz London. But Overbeek and Verwey found that at separations beyond a few nanometres the strength of the attraction declined more quickly than London's theory predicted.

Overbeek correctly suspected that the difference was caused by the finite speed of light. A fluctuation in the electromagnetic field of one of the bodies cannot be felt by the other faster than the time taken for an electromagnetic wave to propagate between them. This means that it becomes necessary to take into account the electromagnetic fluctuations of the vacuum too. But Overbeek lacked the theoretical knowledge needed to tackle that problem, and so he approached Hendrik Casimir for help.

In collaboration with Dik Polder, also at Philips, Casimir calculated how this delay alters the character of the attractive force. In 1948, Casimir worked out the theory for two 'ideal' metal plates (which reflect light perfectly) separated by a gap. But no real material behaves this way, and in the 1950s Evgeny Lifshitz and his co-workers in the Soviet Union worked out how the theory is modified when some light gets absorbed by the materials. This allowed the Casimir force to be generalized to a broad class of materials, including insulators.

The theory correctly describes the attractive interaction that results from quantum fluctuations at all separations, covering both the Casimir (long-range) and van der Waals (short-range) regimes. Arguably a lot of subsequent confusion could have been avoided if these two 'forces' hadn't acquired separate names, as they are ultimately derived from the same cause.

Overbeek didn't succeed in measuring the Casimir force until 1978, when he detected it between a small metal sphere and a metal plate. But accurate measurements that could be compared closely with theory had to wait for another two decades. **P.B.**

to induce 'Casimir levitation', which might be used to make friction-free micro-bearings. It could also provide routes for avoiding Casimir-induced stiction in microengineering.

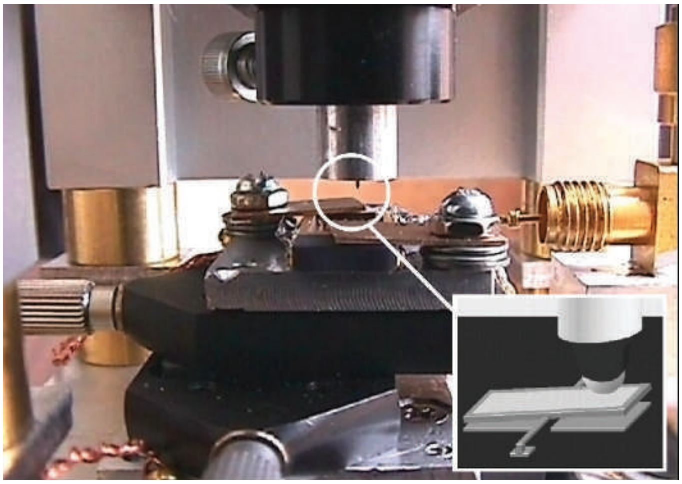
Because the Casimir force stems from electromagnetic fluctuations, it is sensitive to the way materials interact with light. So optical properties such as birefringence, in which the refractive index is different in different directions, can also affect the force. This means that the interaction between two birefringent plates should depend on their orientation: the plates will tend to align with each other. If they are moved out of alignment, a torque will act to restore it.

Capasso hopes to observe this effect by suspending a birefringent disk over a plate, perhaps levitating it using a repulsive Casimir force[1,7]. "We can give the disk a kick with laser light, then shut off the light and watch it rotate back," he says. It should be possible to detect this rotation by looking at how light bounces off the disk. Capasso and his colleagues are planning an experiment like this, using disks of barium titanate tens of micrometres across suspended in ethanol above a calcite crystal.

Attractive proposition

Capasso thinks that such studies could bring together hitherto separate communities — those who work on quantum optics and electrodynamics, and those who work in materials physics. He suspects, for example, that interesting things might happen to the Casimir force close to phase transitions in materials that alter their electronic or optical properties — such as the transition between an insulating and a metallic material, or between a normal metal and a superconductor. His group is currently looking for these effects in the interaction between a gold sphere and a thin slab of a high-temperature superconductor. Any such effect is likely to be small, but he thinks it is worth a try.

> **"It is very difficult stuff — you have to be paranoid about possible sources of error."**
> — Federico Capasso


Balancing act: this device allowed the Casimir force between a metallic see-saw and a spherical electrode (inset) to be measured.

J. MUNDAY/F. CAPASSO

A former co-worker of Capasso, Davide Iannuzzi, now at the Free University of Amsterdam, proposed one such experiment that involved measuring the force between a gold plate and a sphere coated with stacked thin films of magnesium and nickel, which switches from being reflective to transparent when exposed to hydrogen. To their surprise, the researchers saw no change in the strength of the force on adding hydrogen[8] — they had expected the change in the material's reflectivity to affect the Casimir force. "It was a negative result that probably told us more than a positive result would have," says Capasso. One explanation may be that for this material, wavelengths much longer than the visible range contribute significantly to the Casimir force, and that adding hydrogen doesn't alter the reflectivity much at these wavelengths.

So, as they continue to investigate this quirk of nature, researchers are finding that the Casimir force is more slippery than they first imagined. But this exploration of how, and how much, empty space can be engineered has only just begun. It looks sure to demonstrate that there's a lot you can make out of nothing. ■

Philip Ball is a consultant editor for *Nature*.

1. Capasso, F., Munday, J. N., Iannuzzi, D. & Chan, H. B. *IEEE J. Select. Top. Quantum Electr.* **13,** 400–414 (2007).
2. Lamoreaux, S. K. *Phys. Rev. Lett.* **78,** 5–8 (1997).
3. Serry, F. M., Walliser, D. & Maclay, G. J. *J. Appl. Phys.* **84,** 2501–2506 (1998).
4. Buks, E. & Roukes, M. L. *Phys. Rev. B* **63,** 033402 (2001).
5. Chan, H. B., Aksyuk, V. A., Kleiman, R. N., Bishop, D. J. & Capasso, F. *Science* **291,** 1941–1944 (2001).
6. Munday, J. N. & Capasso, F. *Phys. Rev. A Rapid Comm.* (in press); preprint at http://arxiv.org 0705.3793 (2007).
7. Munday, J. N., Iannuzzi, D., Barash, Y. & Capasso, F. *Phys. Rev. A* **71,** 042102 (2005).
8. Iannuzzi, D., Lisanti, M. & Capasso, F. *Proc. Natl Acad. Sci. USA* **101,** 4019–4023 (2004).