Prodding the cosmic fabric with nanotechnology

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Scanning probe microscopes have become vitally important instruments throughout nanotechnology. It has been discovered recently that these same tools can address a much more fundamental question that takes us back to the ancient Greeks and their philosophical discussions regarding the nature of ‘the void’. The concept of the atom as a building block of matter, proposed by Leucippus and Demokritos 2,500 years ago, requires as part of the package a void in which the atoms move. In fact it was probably the philosophical problems associated with having a void that killed off the ancient atomic theory, which was a tragic lost opportunity, as the modern version didn’t re-emerge until the work of John Dalton 2,300 years later.

Although atoms are now a familiar part of the scientific landscape, the true nature of the void remains somewhat mysterious. In classical physics the void is assumed to be a simple absence of all matter and all energy—pure space that has been emptied of everything detectable. This idea of pure space, as an undetectable container of all things we *can* detect didn’t just cause the ancient Greeks problems. More recently Newton struggled with the same concept and in the end simply stated:

> “*I do not define time, space, place, and motion, as they are well known to all. Absolute space by its own nature, without reference to anything external, always remains similar and unmovable.*”

In the same way he also thought in terms of an absolute time. Later statements showed that he wasn’t altogether happy with these definitions, which were more a matter of pragmatism so that he could get on with developing the rest of his scientific framework. Einstein showed that empty space is not just the three dimensions of space but has to incorporate the time dimension to produce empty ‘space-time’, which itself ‘curves’ to generate gravity. The idea of an empty container of matter and energy, whether it is composed of three or four dimensions, is becoming increasingly hard to maintain in the face of the newly discovered ‘dark matter’ and ‘dark energy’ that appear to be invisibly present in the empty container even when everything detectable has been removed.

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A more accurate picture of the void that has emerged from quantum mechanics, or more specifically quantum field theory, is that rather than being an empty container, space or spacetime is a 'something' (precisely what remains a mystery) that itself generates all the particles and energy that we can detect as a result of being stimulated in the right way. Energy manifests itself as particles, so in the following discussion 'particle' means both matter and energy. According to the modern view the 'something' that is the void is a set of 'fields' each of which has an intrinsic, or 'zero-point', energy and is able to generate its own specific type of particle as an 'excitation'. Thus the electromagnetic field makes photons, the electron or 'Dirac' field makes electrons, etc. A simple analogy is to imagine a perfectly still ocean with no waves. If it is stimulated with a very simple excitation, say a small pebble, it produces a wave, which in the quantum view is a single particle. Suppose we somehow had produced a very complicated stimulation that produced huge numbers of particles that interacted and combined in such a way as to produce a conscious intelligence. This conscious intelligence could build particle detectors that would detect simple waves and set up a formalism to describe them. To this intelligence, the world would be composed of particles, or simple waves, and a complete absence of (detectable) waves, which it would call the void. To another being that lived in more dimensions and could see the whole picture however, this absence of waves would not be a void, it would be a vast ocean—just calm. In the same way quantum field theory tells us that an absence of particles and energy (or the void) is simply the condition when all the fields are quiet and unstimulated. In this condition, all the fields still contain an intrinsic energy, the 'zero-point' energy that we have no way of detecting directly.

In this way of looking at things we can revisit the idea of the atom and the void. In the period covering the time of Demokritos through to the development of quantum field theory in the 1930s and 1940s the atom was a particle (as we now know, itself composed of smaller particles) moving in a void. For the last few decades the scientific picture is that a few excitations in the fields that compose the void generate the electrons, protons and neutrons that make up the atom, which interact with each other by exchanging force particles that are themselves generated by the void. This clump of excitations is the atom and it is not something separate that moves around in a void. It is itself part of the void. Figure 1 provides a simple illustration of the different points of view.

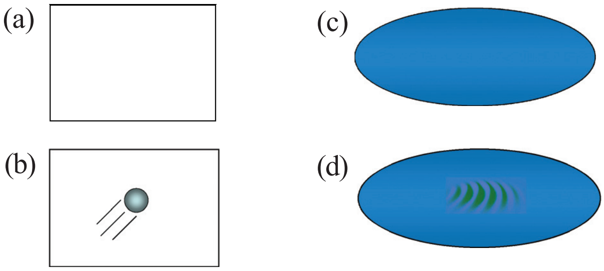

Figure 1. Classical and quantum view of the void.
(a) In classical physics, the void is an empty, but nevertheless real, container that provides an absolute reference for motion. (b) A particle is a separate object that can move through the empty container. (c) According to quantum field theory the void is a set of fields, with a huge zero-point energy density, that are capable of vibrating, with an elementary vibration corresponding to a particle. For example, the electromagnetic field can manufacture photons. The perfect vacuum is the condition in which the field is not vibrating. (d) A single particle is a single elementary vibration (excitation) in the field.

Let us now focus the discussion on the zero-point energy of the fields that compose the void, and to simplify matters consider just one field, the electromagnetic field that makes photons. These are the fundamental particles of light and you can consider a beam of light as being a beam of photons, each one of which is an excitation in the underlying electromagnetic field. So what is the nature of the raw unexcited field with no photons? Again a simple analogy may help here. You can consider the electromagnetic field as being a quantum piano, where each string can vibrate to produce photons (Figure 2). Since the field can vibrate at any frequency the quantum piano (or harp) has an infinite number of strings infinitesimally close together. The thing that makes it a quantum piano is that the strings cannot vibrate with any amplitude, only at fixed amplitudes ascending in a sequence. If we then pluck just one string so that it vibrates at its smallest allowed amplitude, this corresponds to a single photon at the string frequency. If we pluck it slightly harder it vibrates at its next highest allowed amplitude, which corresponds to two photons at that frequency. If we hit it with a wide hammer that stimulates many strings with varying amplitude we create a multitude of photons at a range of frequencies. This is what we are doing when we switch on an electric torch. The chemical energy in the battery heats a wire and the vibrating atoms in the wire stimulate the electromagnetic field to create a large number of photons.

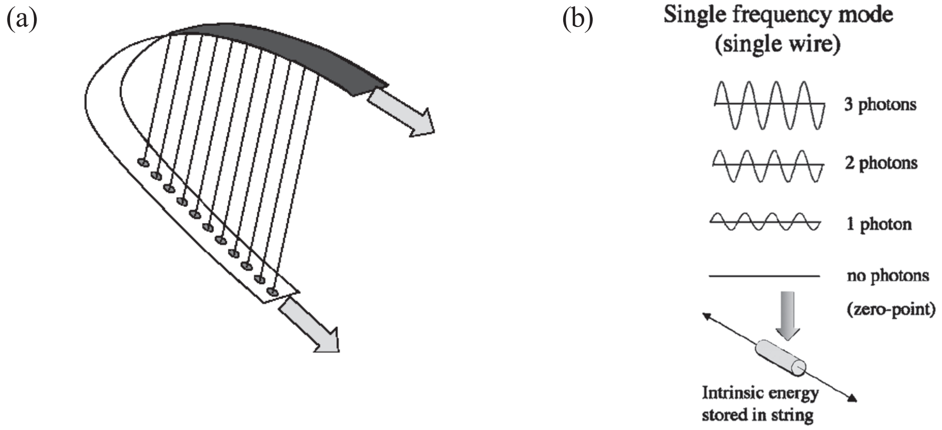

Figure 2. Quantum piano.
(a) The electromagnetic field can be represented by a 'quantum piano' in which, each frequency that the field can vibrate at is represented by one string. For an accurate representation there would have to be an infinite number of strings infinitesimally close together since the field can vibrate at any frequency. (b) A single wire represents a single vibration frequency or 'mode' of the field and since it is a quantum field the vibration amplitude can only take certain values. Thus the lowest possible vibration amplitude corresponds to a single quantum, which manifests itself as a particle, that is, a photon in the case of the electromagnetic field. The second lowest allowed vibration amplitude is two photons in that mode, etc. A string not vibrating at all generates no photons but it still has an intrinsic tensile energy, which gives it the capability of vibrating. This can be considered as the zero-point energy of the string (or field mode). Thus a completely quiet piano, generating no particles, constitutes the void but it still contains an (infinite) zero-point energy.[1]

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[1] This analogy was originally devised by Dr Mike Ward, Deptartment of Engineering, University of Birmingham, UK.

Suppose we now quieten everything down so that none of the strings are vibrating. According to quantum field theory each string still has an intrinsic or zero-point energy, and in the case of our piano this can be considered to be the tensile energy stored in the string that gives it the capability to vibrate. Each string has a fixed zero-point energy and since there is an infinite number of strings (or modes) the zero-point energy of the whole piano is infinite. It is the same with the electromagnetic field. Each mode, or frequency at which the field can vibrate, has a fixed zero-point energy, which can be considered to be the energy that gives the field the capability to vibrate. So with an infinite number of modes the field has an infinite zero-point energy.

Whenever an infinity is encountered in describing a physical system it is an indication that something is wrong with our conception of the system or that something is missing. This isn't simply down to our little brains being unable to imagine the concept, it is also due to the fact that infinity introduces an arbitrariness that removes our ability to describe a system. The possible missing element in this case is the so-called Planck scale, which sets an ultimate limit on the smallest length that has meaning, which is about 10^{-35} metres. The Planck length thus also defines the shortest wavelength (highest frequency) photon that can exist (that is, our quantum piano has a shortest string) and this brings the zero-point energy to a finite but staggeringly large value of 10^{115} J/m^3. Just to get this in perspective, it suggests that the total energy output throughout their entire life of all the stars in all the galaxies in our observable universe could be obtained from a region of empty space considerable smaller than an atom. It is not infinity but still way beyond our imagination. This huge number, derived from one pillar of modern science, is also in massive contradiction to the average energy density of empty space of 10^{-9} J/m^3 derived from the other pillar of modern science, namely general relativity. This discrepancy of more than 120 orders of magnitude between the two great formalisms remains something of an embarrassment. Modern unification approaches such as string theory**[2]** are attempting to solve this discrepancy and unite the two pillars.

This esoteric discussion may seem far removed from nanotechnology but it turns out that there are subtle measurable consequences of the zero-point energy that require the tools of nanotechnology to detect them, and in an ironic twist these same subtle consequences could turn out to be the answer to one of the fundamental problems of getting nanomachines to work. In 1948 a Dutch physicist, Hendrik Casimir, pointed out that placing two perfect mirrors facing each other in empty space would disturb the zero-point electromagnetic field. This is because in such a region, only certain wavelengths (those that fit exactly into the space between the mirrors) are allowed. If only certain wavelengths of real photons are allowed then something must have happened to the zero-point field that forbids it to generate other wavelengths of photons. It is as if something had removed strings from the quantum piano. The zero-point energy density must therefore be lower in the region between the mirrors than outside and this difference in energy will depend on the distance between the mirrors. An energy that depends on distance equals a force and so Casimir's simple prediction was that two mirrors in empty space would attract each other.**[3]**

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[2] For a good description of string theory aimed at non-specialists, see: Brian Greene, *The Fabric of the Cosmos*, New York: Alfred A. Knopf, 2004.

[3] H.B.G. Casimir, *On the attraction between two perfectly conducting plates*, Proceedings of the Royal Netherlands Academy of Arts and Sciences, **51** (1948) 793.

This appears at first hand to be an easy thing to test, especially as the force can be quite large at very small distances; for a 10 nm separation of the mirrors, for example, the pressure on them is comparable to atmospheric pressure (10^5 N/m^2). The force however drops very rapidly with distance (as the inverse fourth power of separation for perfect mirrors) and becomes very hard to measure at separations above 1 μm. Until recently it was technically impossible to set up an experiment to accurately measure the force between two sufficiently flat and sufficiently smooth parallel surfaces that can approach each other to within sub-micrometre distances. An early attempt by Marcus Sparnaay to measure the Casimir force in 1958 using a spring balance[4] succeeded in confirming its existence but he was not able to measure it with sufficient accuracy to compare its magnitude with theory. Casimir's theory made the assumption that the mirrors were perfect, i.e. totally reflecting at all wavelengths. The theory was extended in 1956 by Lifshitz[5] to include real mirrors made out of real materials. In 1997 Steve Lamoreaux at the University of Washington, Seattle measured the Casimir force between a metal sphere and a metal plate using a very sensitive torsion balance.[6] The sphere-plate geometry (see Figure 3) produces a smaller Casimir force at a given separation but it can still be rigorously calculated and it gets rid of one of the big experimental problems with flat plates, namely maintaining perfect parallelism down to tiny separations. Lamoreaux's measurement agreed with theory to a precision of better than 10% and the strange Casimir force arising from nothing but empty space became a rigorously established experimental reality.

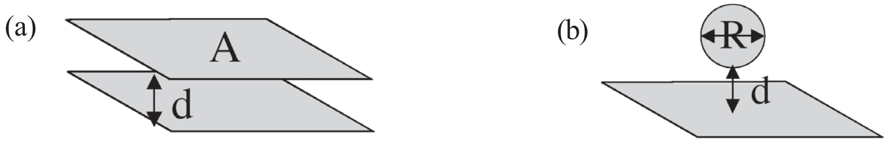

Figure 3. Plate-plate and sphere-plate Casimir force measurements.
(a) For perfect parallel reflectors the Casimir force depends only on the area *A* of the plates, the distance *d* between them, and the universal constants *c* (the speed of light) and *h* (Planck's constant). (b) In the sphere-plate geometry the Casimir force depends only on the diameter *R* of the sphere, the gap between the sphere and the plate and the same universal constants. The magnitude of the force for a given value of *d* is less in the sphere-plate configuration, however it removes one of the experimental problems, i.e. maintaining perfect parallelism of two flat plates at sub-micrometre separations.

Enter the tools of nanotechnology. A device for measuring small forces at small separations *par excellence* is the atomic force microscope (AFM). Its utilisation in Casimir force measurements was pioneered by Umar Mohideen at the University of California Riverside[7] (see Figure 4) and since 1998 a raft of measurements between spheres and plates using AFMs has been reported and the agreement between theory and experiment has steadily improved, though the actual figure for the accuracy is still generating discussion in the literature. The quest for

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[4] M.J. Sparnaay, *Measurements of attractive forces between flat plates*, Physica, **24** (1958) 751.

[5] Evgenii M. Lifshitz, *Theory of molecular attractive forces between solids,* Soviet Physics JETP, **2** (1956) 73.

[6] S. K. Larmoreaux, *Demonstration of the Casimir force in the 0.6 μm to 6 μm range*, Physical Review Letters, **78** (1997) 5.

[7] Umar Mohideen and Anushree Roy, *Precision measurement of the Casimir force from 0.1 to 0.9 μm*, Physical Review Letters, **81** (1998) 4549.

greater accuracy in the measurements is important since it can set limits on parameters in new unification theories attempting to combine general relativity and quantum mechanics, and develop a theory of quantum gravity. Thus the AFM, a tool of nanotechnology, has become a probe of fundamental aspects of the quantum vacuum.

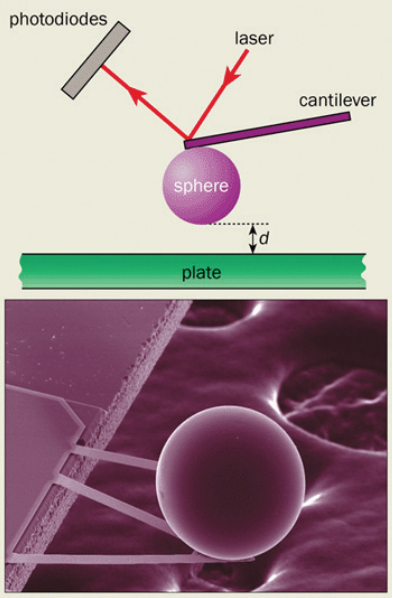

Figure 4. AFM measurement of the Casimir force. The method for measuring the Casimir force with an AFM is shown schematically in the top figure. The AFM cantilever has a gold-coated sphere glued onto the end instead of having a sharp tip as is normally used to scan a surface topography. The deflexion of the cantilever is determined in the usual way, that is, a laser beam is reflected from the back of a cantilever and the deflexion of the reflected beam measured by a position-sensitive detector. The bottom picture shows the 200 μm diameter gold-coated polystyrene sphere and cantilever used in the Mohideen experiment [6]. Reproduced with permission from the Institute of Physics physicsweb pages (http://physicsweb.org/articles/world/15/9/6).

From the opposite point of view the Casimir force has acquired great practical significance in micro- and nanoscale mechanical devices. As the size of these devices has decreased they have become full of boundaries with sub-micrometre gaps where the Casimir force becomes dominant. In fact it is a significant problem in so-called NEMS (Nano-Electro-Mechanical Systems) devices, because while one can take measures to prevent capillary and electrostatic forces there is nothing that can be done to prevent the Casimir force as it arises from the fundamental properties of the vacuum. It thus generates a fundamental and ever-present stickiness of components in micro/nano machines.

More recently, research on Casimir forces has started to investigate the possibility of turning the problem on its head and utilizing the Casimir force as a useful method to transmit force without physical contact. The first real demonstration of the use of the Casimir force to modify the motion in a micromechanical system was performed in 2001 by Frederico Capasso and his team at Bell Laboratories, New Jersey.[8] They built a standard micromechanical device consisting of a flat silicon plate with dimensions of a few hundred μm, suspended by a torsion wire above a surface (see Figure 5). By applying an AC voltage to the pads underneath the plate it could be made to oscillate seesaw fashion at a frequency of a few kHz. Then, using an AFM-type manipulator they lowered a 100 μm gold-coated sphere towards one side of the oscillating plate

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[8] H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop and F. Capasso, *Nonlinear micromechanical Casimir oscillator*, Physical Review Letters, **87** (2001) 211801.

to within a few hundred nanometres. The Casimir force between the sphere and the plate caused a shift in the frequency of the oscillator. They found that the amplitude and frequency shift of the oscillator were measurable with only a few nanometres' change in the height of the sphere.

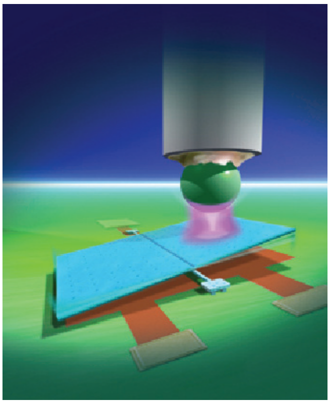

Figure 5. Using the Casimir force in micromachines. Demonstration of the use of the Casimir force to modify the frequency of a micromechanical oscillator by using AFM technology to bring a gold-coated sphere to within a few hundred nanometres of one side of a torsion oscillator [7]. Reproduced with permission from the work of Frederico Capasso (2007).

Another important step towards using the Casimir force was taken in 2002, when the Mohideen group demonstrated a lateral force between a corrugated surface and a similar corrugation imprinted onto a gold-coated sphere[9] (see Figure 6). When the sphere is moved parallel to the corrugation a lateral force that tends to drag the corrugated surface in the same direction is generated through the vacuum.

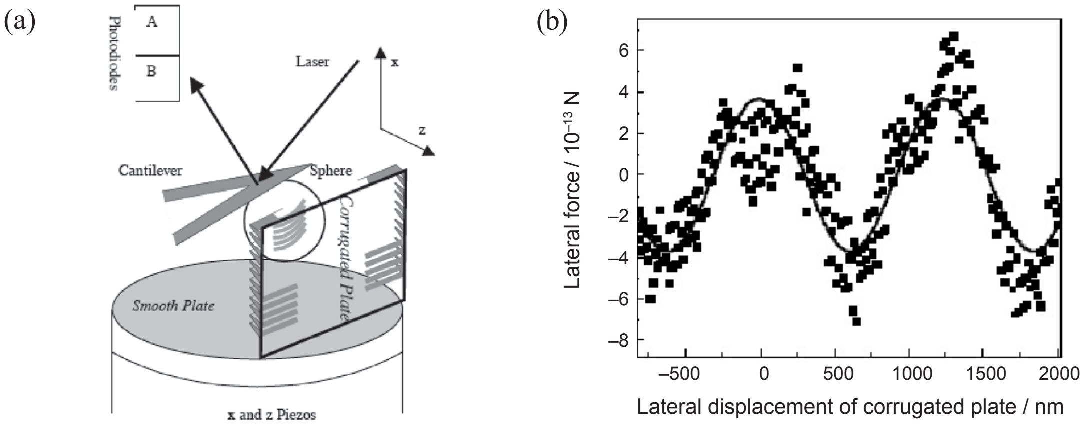

Figure 6. Lateral Casimir force.
(a) Demonstration of the lateral Casimir force transmitted through vacuum between a corrugated surface and a sphere with the same corrugation imprinted onto it. (b) Pulling it past the surface generates a lateral force that oscillates as the corrugations move past each other. Figure reprinted with permission from F. Chen and U. Mohideen, Physical Review Letters, (2002) 88 101801; http://link.aps.org/abstract/PRL/v88/p101801 (copyright (2002) by the American Physical Society).

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[9] F. Chen and U. Mohideen, *Demonstration of the lateral Casimir force*, Physical Review Letters, **88** (2002) 101801.

Could this be the answer to the stickiness problem in nanomachines? The basic idea for a simple rack and pinion is shown in Figure 7. A rack is moved laterally at a distance of a few tens to hundreds of nanmometres away from a pinion and a force is transmitted through the vacuum to rotate the pinion. It could be as simple as finding the right combination of materials and the right shape of corrugations to make this kind of machine a practical reality. In fact the lateral Casimir force may be of far more use than a passive force transmission mechanism. The theory of the Casimir force in cavities is highly developed only for very simple geometries such as the plate-plate and sphere-plate systems. For a complex system such as the one shown in Figure 7 it is still under development. A recent paper however[10] indicates that the strength of the force transmission and even the direction of the force depends on the speed at which the rack is moved. Thus if it is moved backwards and forwards at different speeds in each direction it may be possible to provide a continuous unidirectional torque on the pinion.

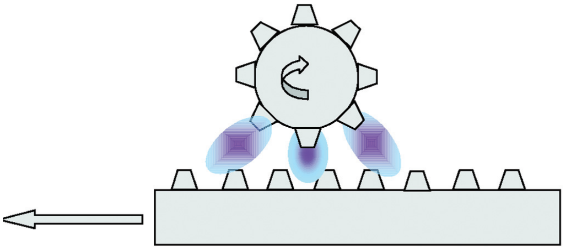

Figure 7. Non-contact rack and pinion.
The lateral Casimir force can be used as a method of transmitting force without contact as in this rack and pinion.

This is a particularly useful action mechanically as it is a method to transfer oscillatory motion into unidirectional linear motion. This is what a car transmission system does when considered all the way from the oscillating pistons through to its linear motion along a road. An alternative method of achieving this has been suggested by another recent paper,[11] and that is to define a system with an asymmetric set of teeth as shown in Figure 8. Then oscillating the two surfaces in the normal direction will provide a unidirectional linear force, whose direction can be varied by altering the lateral displacement of the two sets of teeth. This is the so-called *Casimir ratchet* effect.

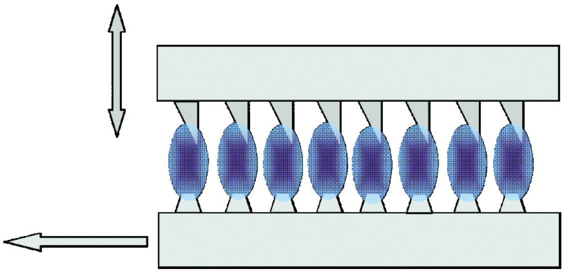

Figure 8. Casimir ratchet.
Using asymmetric teeth on one side, an oscillatory motion of one side in a normal direction can produce a unidirectional motion of the other side.

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[10] Arash Ashourvan, MirFaez Miri and Ramin Golestanian, *Non-contact rack and pinion powered by the lateral Casimir force*, Physical Review Letters, **98** (2007) 140801.

[11] T. Emig, *Casimir force-driven ratchets*, Physical Review Letters, **98** (2007) 160801.

It is early days in research on exploiting the Casimir force for contactless transmission, but it holds the promise of eliminating the stickiness problem in micro/nano mechanical components, hence allowing machines to continue to be scaled down towards molecular dimensions. Of course as gaps in ‘contactless’ transmission get smaller and approach the nanoscale at some point it is reasonable to ask what ‘contact’ actually means. That is, in the system shown in Figure 7 everything is free to move, whereas mechanical components in ‘contact’ stick together. How close together do they have to be for everything to gum up? There is an answer to this question though it is fairly hand-waving. For two perfectly clean surfaces brought right into contact they stick together due to a force known as the van der Waals force, which acts between any two atoms. There is a subtle distinction between the van der Waals and Casimir forces: both spring from the same source, namely the zero-point electromagnetic field, but their theoretical description is different: generally the van der Waals force is described in terms of surface charges on the two bodies whereas the Casimir force is described in terms of the zero-point electromagnetic field. The surface charges however are a result of fluctuations in the zero-point field, hence fundamentally the two forces arise from the same source. As two surfaces are brought together the power law describing how the force varies with distance changes, and this is the crossover between the two régimes. Within the context of this article this crossover can be thought of as the minimum distance between two components before they stick together. This distance is about 10 nm, so the machines shown in Figures 7 and 8 could be scaled down until the teeth were about the size of a large molecule.

In summary, it is clear that the tools of nanotechnology, such as scanning probe microscopes and NEMS devices, can provide important information about the fundamental nature of space, especially the zero-point electromagnetic field. An exciting aspect of this subject is that a better understanding of the force that arises from the zero-point field, i.e. the Casimir force, may enable its control to some extent. This would then feed back into improved NEMS devices that make use of the force either to achieve contactless transmission or for more exotic applications such as the Casimir ratchet.

This article will be incorporated into *A Survival Guide to Nanotechnology* by C. Binns, to be published by Wiley in 2007.