Alex Rodriquez, *left*

Steven Johnson, *right*

John Joannopoulos

ATTRACTIVE REPULSION

An innovative numerical approach makes possible new insights into a fascinating quantum effect called the Casimir force

If opposite charges attract and like charges repel, what happens between neutral objects, ones that have no charge? They maintain their distance in a perpetual standoff, right? Not in the quantum universe, where space between objects bubbles with "virtual" particles and anti-particles of evanescent lifetimes that can cause even neutral objects — when they're close enough — to move nearer to each other. It's called "the Casimir effect" after Dutch physicist Hendrik Casimir, who in 1948 first calculated the attractive force between two neutral metal plates about a micrometer apart.

Since Casimir's original work, physicists have struggled to understand the forces between surfaces that aren't flat — a flat plate and a sphere, for instance, and beyond that to general geometries. "The problem has been so difficult," says Steven Johnson, MIT professor of mathematics, "that many researchers have employed drastic approximations to get some answer that they hope will be at least crudely correct."

In the last year, Johnson and physics grad student Alex Rodriquez and others who work with MIT professor John Joannopoulos have employed a numerical approach that is shattering long-held notions about the Casimir effect. Using BigBen, PSC's Cray XT3, they have carried out simulations that calculate an "exact" solution. Their method depends for its accuracy only on the availability of enough computational power. Moreover, it is independent of materials or geometry, so it can be used to study the Casimir forces in any system.

One of their important findings is that the Casimir force between two purely metal objects can be *repulsive*. In recent work with cylinders within cylinders, furthermore, they've for the first time demonstrated the possibility of stable, Casimir-force induced suspension between objects. "The possibility of repulsive forces is especially tantalizing," says Johnson, "because it raises the prospect of quantum levitation — suspension of mechanical parts in air or fluids purely from quantum fluctuations, without the device having to supply power." A levitating sphere of this sort, for instance, could serve as a frictionless bearing in a microelectromechanical system, aka MEMS.

To arrive at this fascinating finding has involved heavy-duty computation. "Computing these forces using *approximations* is hard," says Rodriguez, "but we're using *exact* Casimir forces, and the geometries we've been looking at lately are big." Referring to work at PSC between April and July 2008, says Rodriguez, "We essentially used up a year's worth of supercomputing in three months. They were very expensive calculations, and the results are very interesting."

A FROTH OF PARTICLES

For Casimir's original calculation — two parallel, flat-metal plates — the problem is, relatively speaking, easy. "There is a teeming froth of virtual particles," explains Rodriquez, "that cause these two plates to feel a pressure." You get a feel for this effect, he says, by thinking of the quantity of virtual particles outside the plates as exceeding those between the plates, so that pressure on the outside surfaces pushes the plates together.

Other geometries, however, become demonically complicated, and most previous attempts to model the Casimir force have used some version of an approximation known as "the proximity force approximation" (PFA) to make the calculations feasible. The PFA assumes any object is composed of tiny, discrete chunks of material, and these chunks interact only in pairs. In reality, however, other nearby chunks in the object also interact, and the PFA can drastically underestimate or overestimate the Casimir force.

In 1965, Russian physicist Evgeni Lifschitz developed a better approach. By carefully framing the problem in terms of electromagnetism, Lifschitz provided a mathematical tool that the Joannopoulos group turned to in their recent work.

Lifschitz's math involves solving Maxwell's electromagnetic equations for a point-source of electricity. Think of it, says Johnson, as calculating the electric field surrounding a tiny antenna through which an electric current is flowing. Physicists call this the Maxwell Green's function, a problem involving partial differential equations (PDEs). In this case, the supercomputer first solves many PDEs to obtain the electric-field value at a large number of points (tiny antennas) surrounding the surface of an object over a wide range of electromagnetic frequencies.

Summing these electric-field values yields an approximate value for the Casimir force. If this process is repeated many times, the solution eventually converges to the exact value. Accuracy depends only on the computational power and time available. "Unlike many earlier approaches to Casimir forces, we weren't forced to sacrifice generality for the problem to be solvable," says Johnson. "We were able to trust that the supercomputer could handle the most general possible problem and leave us free to explore geometries limited only by our imaginations."

BigBen is well suited, says Johnson, for this kind of calculation. "The Cray XT3 provided us with a good combination of many processors and relatively powerful individual processors."

REPULSIVE RESULTS

Letting their imaginations roam, the Joannopoulos group tried a geometry that looks like a zipper — two parallel plates with interleaving metal brackets. After setting the separation distance between the two plates, they concentrated 1,024 processors of the Cray XT3 on a circular space a few micrometers in diameter surrounding the surface of a bracket. Then the parallel plates of the zipper were moved closer together, and the process repeated, many times over.

The zipper model showed for the first time that the Casimir force could be repulsive between metals (see sidebar), a major result long suspected but impossible to prove without an exact numerical solution. Ironically, the repulsion results from attraction between sub-parts of the system. "No one had investigated this structure before," Rodriguez says, "nor demonstrated repulsive forces purely between metals."

Expanding on this discovery, the researchers recently studied an even more complex system — cylinders within cylinders, separated by a liquid (ethanol). The outer cylinder is metal, while the inner cylinder is silica, a semiconductor. To show that their method is independent of geometry, the team ran the simulation both with circular and square cylinders.

The results showed not only a repulsive force between the metal and the silica, but also that this force is stable — the inner cylinder is effectively "levitating" inside the metal cylinder. Such stable structures could act as frictionless bearings in a MEMS device, or as an oscillator in a switch.

New understanding of a remarkable direct manifestation of quantum fluctuations as a measurable force.

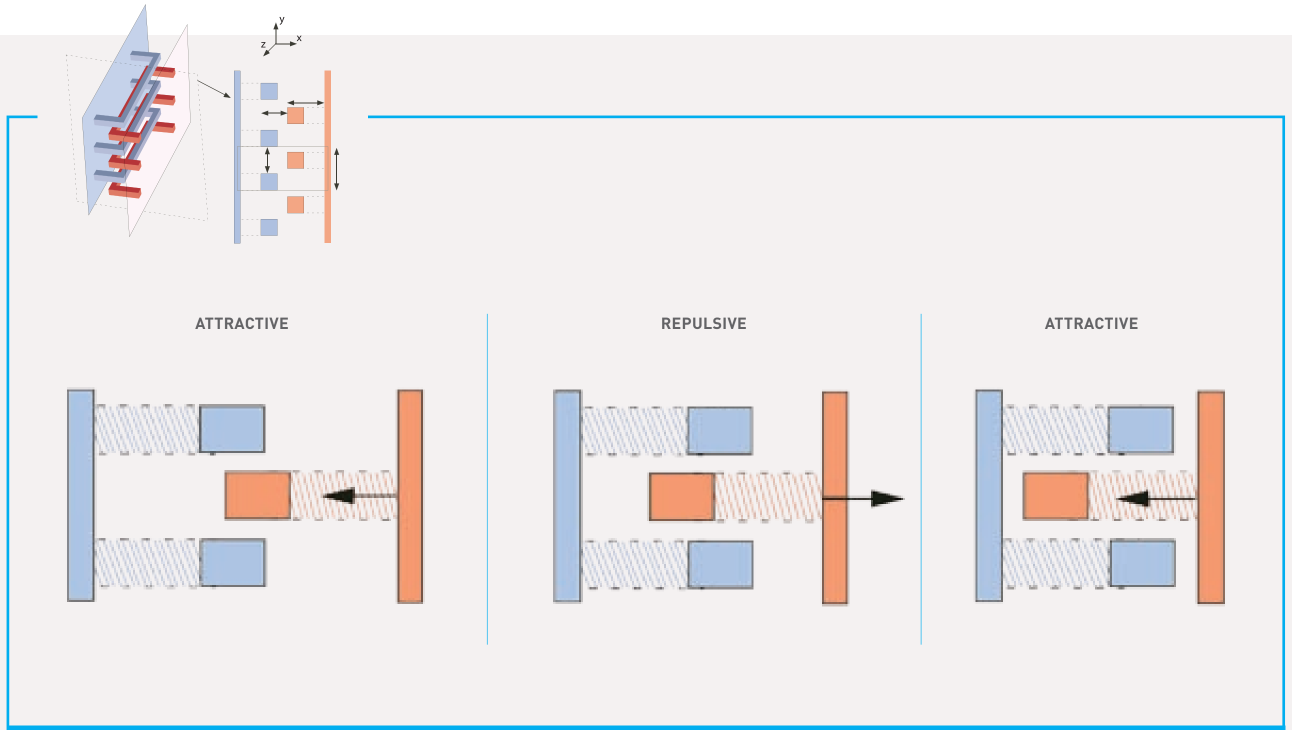
The greatest benefit of understanding the Casimir force may occur when MEMS systems evolve into nanoelectromechanical systems. The Casimir force in devices with parts separated by nanometers can cause moving parts to stick together and the device to grind to a halt — called *stiction*. "Casimir forces are thought to be a significant contributor to stiction in the smallest devices," says Johnson, "and a better understanding of these forces could lead to devices that operate more smoothly."

Even if there were no practical applications, the Joannopoulos group would continue to study Casimir forces. They are interested in the physics of the "froth of virtual particles" that may be better understood with their ability to model Casimir forces exactly. "These forces," says Johnson, "are a remarkable direct manifestation of quantum fluctuations as a measurable force."

One of the possible phenomena they want to look for is a geometry that results in repulsive Casimir forces not due to attraction of sub-parts of the system. Such a purely repulsive geometry, if it exists, will require much more of BigBen's time. **[TP]**

MORE INFORMATION

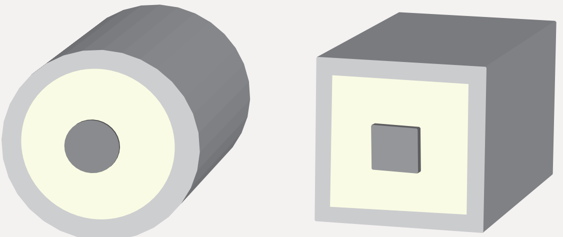
http://www.psc.edu/science/2008/casimirforce.html



ZIPPER GEOMETRY: ATTRACTIVE REPULSION

The 3D schematic (upper left) shows the Casimir "zipper" geometry of interlocking metal brackets (in different colors for illustration only), along with a 2D *xy* cross-section. Dashed-lines indicate that the brackets attach to the plates as shown in 3D.

The three 2D boxes show the transition from attraction to repulsion for this zipper geometry. The repulsive force arises from attractive interactions of the bracket sub-parts of the system. With the parallel plates at relatively large separation, the Casimir force between them is attractive, almost as if the zipper brackets (squares) were not there. When the plates are closer together and the brackets overlap, a strong attractive Casimir force tries to pull the adjacent brackets toward each other, and this attraction resists the attraction between the plates, producing a repulsive force (indicated by the arrow). If the plates are closer yet together, however, the resistance of the brackets is overcome and the overall Casimir force is again attractive.



CYLINDERS WITHIN CYLINDERS: STABLE CASIMIR FORCE

Simulations for these two cylindrical geometries, circular and square, with a cylinder of silica (SiO$_2$) suspended in ethanol inside a metallic cylinder, showed a stable repulsive force between the two cylinders, so that the inner cylinder in effect levitates, presenting the possibility of frictionless bearing in a MEMS device.