The Lattice QCD group members with the IBM BlueGene/L supercomputer (installed in 2006). From left: Lattice QCD group leader Dr. Shoji Hashimoto, Dr. Norikazu Yamada, Dr. Junichi Noaki, and Dr. Hideo Matsufuru.

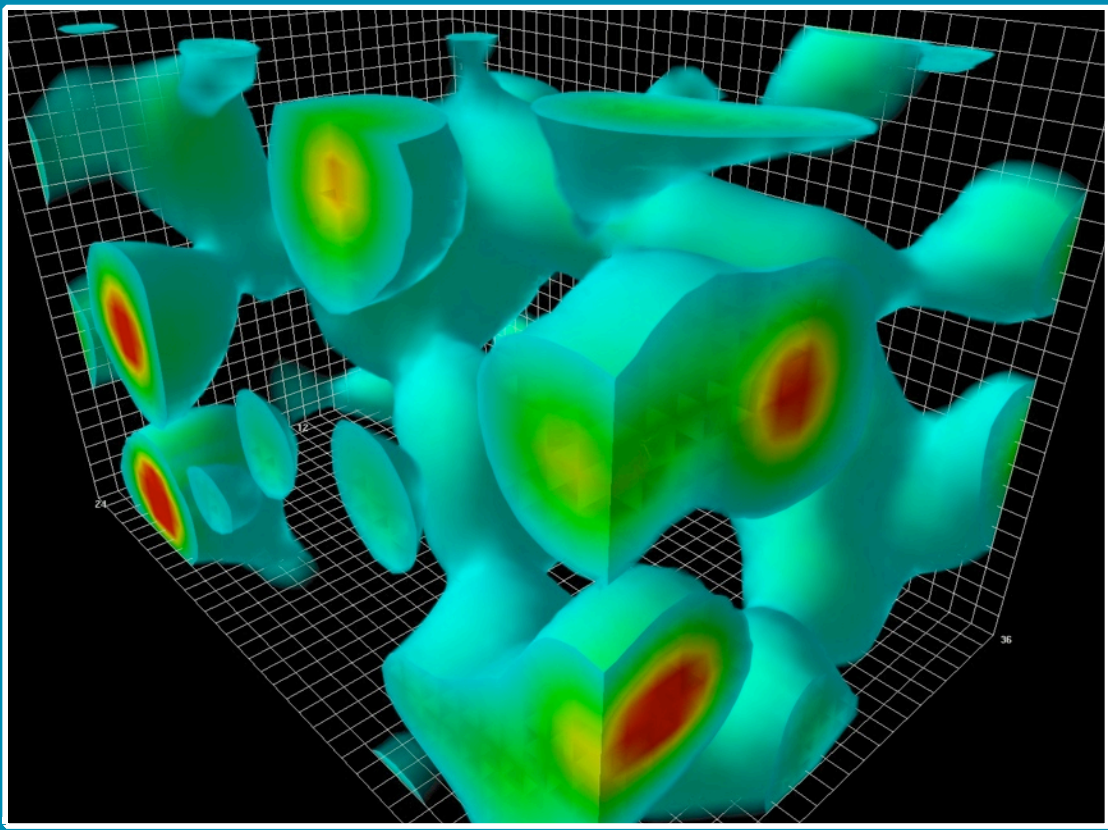
Lattice explains the origin of mass

[Supercomupters, Lattice QCD, Spontaneous Symmetry Breaking]

At the top of the elegant edifice of theoretical particle physics, the theory of quantum chromodynamics (QCD) has received strong support from new computer simulations. The Lattice QCD group at KEK, with the launching of a new project in 2006, became the first to present proof of the mechanism that gives mass to matter. This is just the first of many important results expected to be produced by the new formalism.

Some of the best supercomputers around the world run at full power to create vacuums. These are not ordinary vacuums, not just simple empty space. Instead, these are complex simulations of a theory called quantum chromodynamics, or QCD. This theory describes the interactions among two types of fundamental particles: quarks and gluons. Since these particles interact so strongly with each other, the interaction is called the strong interaction, or the strong force. This, mediated by gluons, is the strongest of the four forces that are known to exist in our universe.

This elegant mathematical formalism of QCD says that vacuums are not actually empty, but instead contain bubbles of quarks and antiquarks that come into and out of existence endlessly. According to QCD, it is in these vacuums (in condensates of quarks and antiquarks, to be more precise) that particles gain mass. QCD, together with the



In quantum field theory, vacuum is not an empty space, but contains bubbles of particles that come into and out of existence endlessly. (Image courtesy of Prof. Derek Leinweber, CSSM, University of Adelaide. http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/)

theories of electromagnetic and weak interaction constitute the Standard Model of particle physics.

Hidden particles

No one has actually seen individual quarks. They are hidden, or confined, within particles called hadrons. 'Hadron' is a name given to a group of composite particles that contain two or more quarks. Common hadrons include particles such as protons, neutrons, and pions. The reason why no free quarks can be seen is that the strong force between quarks, unlike all other known forces, does not become weaker as quarks are separated. In fact, it stays the same, and the work required to rip them apart is enough to produce pairs of quarks and antiquarks from vacuum in between. You would end up creating more quarks by trying to isolate one.

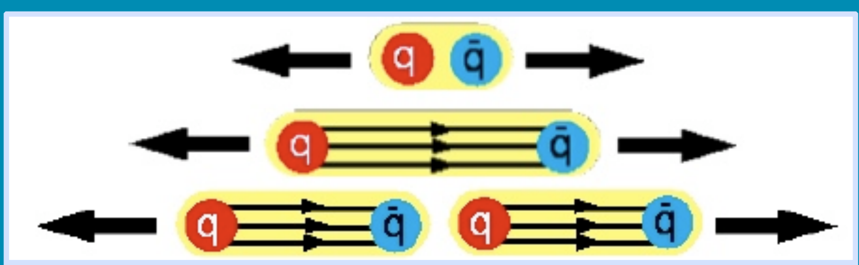
Quarks interact strongly because of a property called color charge. Each quark has one of three 'colors': red, green, or blue (thus the name 'chromo', in analogy with the three primary colors in nature). Just as regular charged particles interact electrically via two charges (positive and negative), quarks interact strongly through these three charges.

QCD explained the mysterious variety of new hadrons that has been observed in laboratories since the 1950s. The success of QCD is clear from the bounty of confirmatory data gathered over the course of the last thirty years.

As successful as it is, QCD theory is extremely hard to solve analytically at low energy. At high energy, the interaction of quarks and gluons becomes relatively weak. This is called asymptotic freedom, and allowed precise predictions of high-energy experimental results by means of usual analytical procedures.

To deal with QCD at low energies, physicists in early 1980s turned to computer simulations. Since computers cannot deal with continuous spaces, researchers approximated space-time as a lattice, a grid of equally spaced points connected by lines. Quarks live on vertices, and gluons reside on links between two vertices.

"Quarks are point-like particles that also behave like waves because of their quantum mechanical nature," explains the Lattice QCD group leader Dr. Shoji Hashimoto of KEK. "At the end of the day, you'd see fluctuating fields of quark and antiquark across the lattice, and what you are looking at is the behavior of vacuums." This approximation to continuous space-time, called lattice QCD, has successfully explained quark confinement (the fact that single quarks are not found in nature) and has produced predictions in excellent agreement with experimental data.



Confinement of quarks

Proton mass calculated

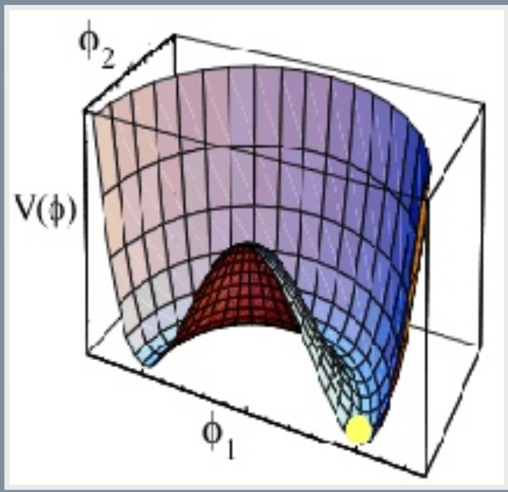
Hashimoto calculates that 30 years of development has made computers roughly a million times faster. He says that it has only recently become possible to do full-scale simulations of lattice QCD, bringing necessary virtual quark-antiquark pair creation into vacuum for dynamical simulation.

Hashimoto and his team of around ten physicists create vacuums, throw various quarks in them depending on their physics purpose, and make analysis sampling

500-1000 vacuums at once.

In April 2007, the team's simulations successfully explained the 98 percent of proton mass expected to come from QCD effect. This was a dazzling-bit of news, because no one had ever before been able to prove the mass of anything from purely the theoretical formalism that explains the origin of mass. Here, for the first time, the mass was derived from the nature of the vacuum based on the fundamental theory of QCD.

"Our new tool was a formalism that allowed us to implement the mass-generating mechanism exactly on our lattice, without approximations," says Dr. Hideo Matsufuru of KEK, a member of Lattice QCD group and supercomputer group.



The wine-bottle potential via which hadrons gain mass.

Chiral symmetry breaking

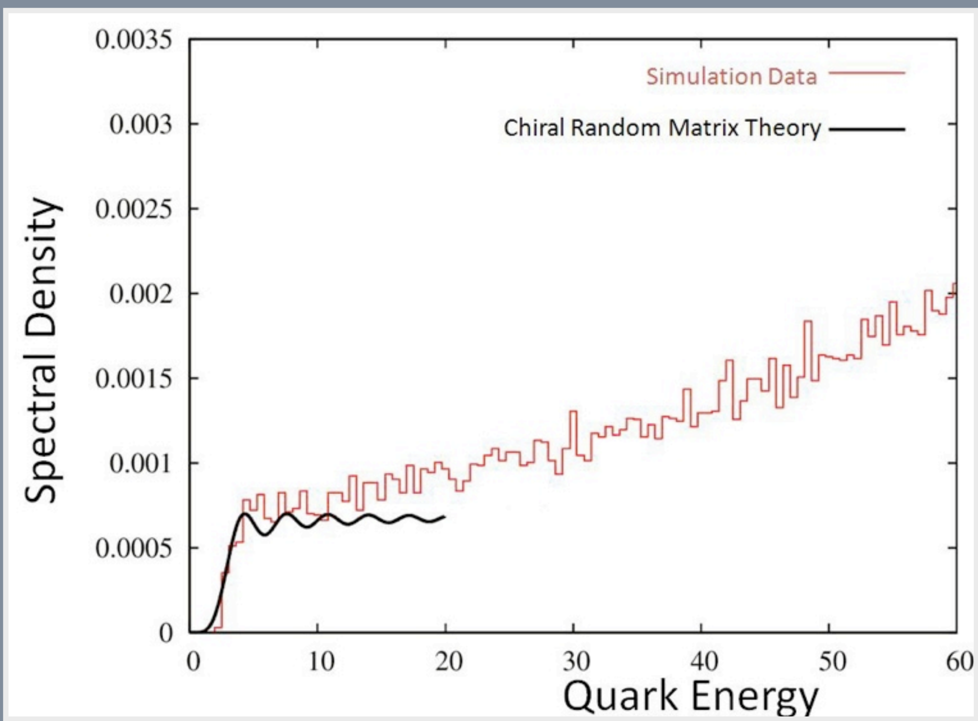
The new tool is called an exact chiral symmetry. Chirality refers to the handedness of a quark field. Each quark spins, somewhat like the Earth. The direction of this spin relative to the direction of motion it gives certain handedness that manifests in symmetry.

Chiral symmetry is said to hold if the left-handed quarks and right-handed quarks transform independently. Mathematically, this is the case when quarks have no masses. A broken chiral symmetry, in turn, is what gives rise to the mass in hadrons. For the case of a proton, quarks constitute only 2 percent of the proton mass, and the rest are governed by the chiral symmetry breaking.

If the chiral symmetry breaking in vacuums causes hadrons to have mass, how does the symmetry break? Imagine an empty wine-bottle (see figure). Set it up and drop a small marble in on the symmetrical potential at the bottom. The marble would land on the tip of the bulge and roll down to one side of the bottom of the well. Notice how the system becomes unsymmetrical when the marble chooses a certain direction to settle onto more stable state. Physicists call this spontaneous symmetry breaking. QCD theorists believe that this is how the chiral symmetry breaks in a wine-bottle shaped potential, giving mass to quark composites.

Lattice QCD with exact chiral symmetry

The difficulty associated with modeling continuous space-time as a lattice was the bottleneck in the formulation of lattice fermion that preserves chiral symmetry. To implement chiral symmetry researchers had to use various approximations, and these produced vast uncertainties that made the calculations involving light-mass quarks and antiquarks unreliable. In order to perform a complete simulation of quarks, however, exact chiral symmetry needed to be in place.



The 2006 simulation successfully obtained the quark and antiquark condensate in which particles gain mass. The spectral density where the spectrum flattens out at the lower end of quark energy shows the density of condensed quark-antiquark pairs.

Then there came the 1998 talk given by H. Neuberger of Rutgers University. He showed that the exact chiral symmetry could be implemented on lattice by introducing an infinite number of extra fermions, a theory called overlap fermions. By adding an extra dimension (as was originally proposed by David Kaplan), he was able to obtain the correct chiral symmetry at low energy beneath the high-energy sea of fermions.

"The first breakthrough since the lattice formulation," according to Hashimoto. This breakthrough allowed a step forward in explaining the experimental value of proton mass.

"We are confident that the mass producing mechanism of the QCD is true," says Hashimoto.

Fast computing

The achievement required advances in many areas.

While the implementation of the exact chiral symmetry was key, also necessary was the new IBM BlueGene/L supercomputer that had fifty times the computing power of the previous machine.

Additionally, researchers worked from the theory, algorithm, and code sides to push the limit of the cpu. Eliminating any singularities (mathematical discontinuities caused by the lattice structure) that unwantedly showed up and took up cpu time was one important optimization.

Algorithmically, they also put much work into simplifying the giant matrix calculations. The final code was optimized by IBM Japan Co. that, in the end, made it run more than a thousand times faster.

The team of physicists from KEK and two institutions in Taiwan are now working on analyses of diverse topics such as quarks' masses, quark seas, and topological susceptibility of vacuums. In these studies, the researchers are making full use of the new chiral symmetry environment.

"For now, we are on the front-line of Lattice QCD with exact chiral symmetry," says Matsufuru. "Soon, other groups from Europe and the US will catch up. Before that happens, we still have many interesting experiments we can do before the next upgrade." They expect next supercomputer in 2011.

Having a working formulation of lattice QCD with exact chiral symmetry means physicists can explore many topics that are deep and fundamental. One example is the simulation of the early universe. In the first 10^{-6} seconds after the big bang, quarks and gluons formed baryons and mesons.

"Understanding this phase transition is crucial in cosmology, and will help us to understand how stars and galaxies are formed," says Hashimoto. "Lattice QCD with exact chiral symmetry is a very strong tool for this purpose."

The world-wide lattice QCD community has become increasingly intrigued by physics beyond the Standard Model. Asked what his future plans are, Matsufuru answers that he and his colleagues are exploring some possible physics beyond the Standard Model.

With the CERN's Large Hadron Collider starting in November, high energy physicists will soon be busy selecting, constructing, and proving viable theories. Lattice QCD will be an important part of such exploratory missions in the decade to come.

Supercomputer systems at KEK. Left: Hitachi SR 11000 K I (2.15 Tflops). Right: IBM BlueGene/L (57.3 Tflops).

Related Link:
[The JLQCD Collaboration]
[KEK Supercomputer System]
[JLDG: Japan Lattice Data Grid]
[International Lattice Data Grid (ILDG)]

HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION (KEK)

Address : 1-1 Oho, Tsukuba, Ibaraki 305-0801 JAPAN
Home : http://www.kek.jp/intra-e/feature/
Mail : misato@post.kek.jp