because the U.K.'s Hadley Center and the Max Planck Institute for Meteorology in Hamburg, Germany, supplied the bulk of the needed simulations.

The crunch in U.S. climate computing "is not a matter of talent," says Cicerone, "it's focus, emphasis, and computer resources." U.S. researchers have long felt at a disadvantage because a trade dispute with Japan has prevented them from buying "vector" supercomputers from Japanese companies like Fujitsu and Hitachi. Instead, U.S. firms have concentrated on massively parallel supercomputers that, despite their much ballyhooed promise, have failed to provide the promised boosts, at least when computing climate change, says Kiehl.

Perhaps more crucial, say U.S. researchers, is the lack of focus on climate modeling. NCAR, NOAA's Geophysical Fluid Dynamics Laboratory, and several other institutions have developed sophisticated global climate models. But at each center, climate change modeling must vie for available computer time with other research on atmospheric science. "It's a matter of dedicating computer hardware to climate modeling," says Kiehl. "We don't do that here. There's also a cultural issue. The competition [among many centers] is viewed as a healthy way to stimulate research. I agree, but the climate modeling field has reached such a level of complexity that we have to change the way we've been working." Both the NRC study and a December 2000 USGCRP report recommend that the country create a center for U.S. climate modeling. The USGCRP report even suggests a "Climate Service," modeled on the Weather Service, that could perform climate modeling and run a climate observing system.

Given the push from the White House, climate scientists are optimistic that the field will get a needed boost. A new 10-year plan for USGCRP that would tighten up management is working its way to Congress, but all eyes are now focused on the Commerce Department. "The secretary is very engaged," says Evans, "and everyone's taking it very seriously, so something is likely to happen."

–RICHARD A. KERR

SUPERCOMPUTING

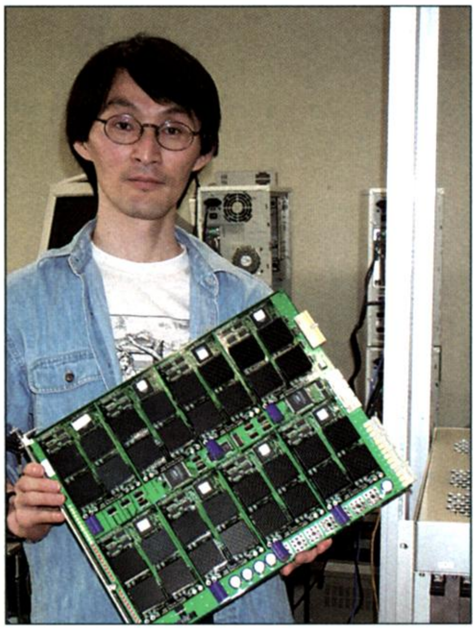
High-Powered GRAPEs Take On the Cosmos

An astrophysicist's dream machine, the GRAPE-6 supercomputer can put virtual galaxies through their gravitational paces

TOKYO—The world's fastest supercomputer is an unimpressive-looking machine with a name like a fruit drink and a price tag to warm a lab director's heart. Meet GRAPE-6, perhaps astrophysicists' most anticipated tool.

Unveiled earlier this week at a symposium* here, GRAPE-6 is the latest in a line of machines that has been quietly revolutionizing astrophysical simulation. Developed on a shoestring budget by a small team of researchers at the University of Tokyo, GRAPEs have become the machines of choice for simulating the formation of planets, the evolution of star clusters, and the collisions of galaxies. They have earned this distinction by being exquisitely tailored to do just one thing: computing the gravitational attraction between two bodies. GRAPEs run through this calculation so quickly that researchers have been able to begin simulating these astrophysical phenomena using realistic numbers of celestial bodies, a task that chokes conventional supercomputers. And GRAPEs are so affordable that even modestly funded groups can buy their own. Many groups have several.

"This is the democratization of supercomputing," says Mordecai-Mark MacLow, an astrophysicist at the American Museum of Natural History in New York City. Simon White, a theorist at the Max Planck Institute for Astrophysics in Garching, Germany, adds that work on stellar dynamics "has been much more lively than it would have been without [GRAPEs]." At least 32 research groups around the world now use them, and the tangle of collaborative work is so thick that Piet Hut, an astrophysicist at the Institute for Advanced Study in Princeton, New Jersey, has to think long and hard to name theorists without some connection to GRAPE simulations. The impact of GRAPE "has been revolutionary," says Hut, who himself collaborates with the GRAPE developers. Despite their limitations—GRAPES alone cannot calculate the effects of temperature, radiation, or magnetism—over the past decade their knack for gravitational number-crunching has helped resolve long-standing questions about planet formation, the behavior of globular clusters, and the collision of galaxies.



Hot item. Astrophysicist Jun Makino shows off a circuit board from the just-unveiled GRAPE-6.

CREDIT: D. NORMILE

And the best may be yet to come. GRAPE-6 debuts as the fastest computer in the world, with a theoretical peak speed of 30 trillion floating-point operations per second—teraflops or Tflops, for short. IBM still claims to hold the record for general-purpose computers, with its ASCI White supercomputer, which operates at 12.3 Tflops.

The GRAPE project grew out of dissatisfaction with available computers. In the mid-1980s, Daiichiro Sugimoto, an astrophysicist at the University of Tokyo, and Jun Makino, one of his grad students, were using so-called *N*-body simulations to study the evolution of star clusters. Makino recalls that simulations involving a few thousand stars took hundreds of hours of supercomputing time. And they wanted to scale up to hundreds of thousands of stars. "We really needed a computer much faster than what was available," Makino says.

The calculation is elementary, equaling the product of the masses of the two bodies and the gravitational constant divided by the square of the distance between the bodies. The problem is that increasing the number of bodies for greater realism increases the number of computations quadratically, because every body interacts with every other body.

Sugimoto's group was unaware that a problem similar to theirs had already been solved just across town. In 1983, Yoshihiro Chikada, an astronomer at Japan's National Astronomical Observatory, completed a special-purpose computer that processed the raw signals gathered by the battery of antennas at the Nobeyama Radio Observatory into usable data. The key idea was to hardwire the routine calculations as

* Astrophysical Computing Using Particle Simulations, 10–13 July.

electronic circuits instead of directing the computer to perform them by software routines. Instead of one line of code executed with each computer clock cycle, the calculation would be completed in the time it took electrons to speed through the circuit. Despite the cost of having these customized chips specially fabricated, they ended up with a machine that was "hundreds of times better in terms of cost-performance" than its alternatives, Chikada says.

It occurred to Chikada that a similar approach might be useful for theoretical simulations. He was too busy to follow up on his own idea, but he circulated an outline of how he thought such a computer would work. And sometime in 1988, this idea reached Sugimoto. Soon afterward, Sugimoto's group started work on its first GRAPE.

Sugimoto and his colleagues relied on off-the-shelf chips and components, which they wired by hand into circuits that would perform the gravitational computation. This kind of hardwired circuit is called a pipeline, which led to GRAvity PipE and to GRAPE. (Makino explains that Sugimoto, who retired in 1997, had wanted a catchy name for their device, and Apple Computer had legitimized the idea of computers with fruity names.) The researchers also decided not to make GRAPE a stand-alone computer. Instead, GRAPEs rely on a front-end computer, a workstation or desktop PC, that keeps track of progress and feeds the data on the mass and location of the bodies to the GRAPE boards for the heavy computing. The forces GRAPE comes up with go back to the front-end computer, which adjusts the positions of the bodies, takes a step forward in time, and starts another computing cycle.

Sugimoto's group completed the first GRAPE in 1989. Running at 120 million flops, GRAPE-1 was slower than the 1-billion-flops (1-gigaflops) capability of supercomputers then available. But they put it together with just $3000 in parts and a year's worth of effort. Best of all, Makino says, "we had it for 24 hours a day." And they used it round-the-clock, producing three or four papers on galactic dynamics over the following year.

They had actually started work on two versions of GRAPE simultaneously, and this set a pattern for future development. Even-numbered generations have higher numerical accuracy and are intended for studying phenomena involving collisions which require very accurate force calculations. Odd-numbered generations are less accurate, less powerful, less expensive, and more suited for studying long-term collisionless processes, such as galactic evolution.

GRAPE-2 was completed about a year after GRAPE-1 and soon yielded its own crop of papers. "We demonstrated we could do interesting science and not just hardware," Makino says. And suddenly, researchers around the world started asking how they could get their own GRAPEs. Sugimoto's group was happy to share its development but didn't want to spend all its time building computers. They now have an agreement with Hamamatsu Metrix, a small electronics firm in Hamamatsu, which builds and sells GRAPEs, returning some nominal level of financial support for research to the University of Tokyo team.

GRAPE-3, the first version widely available to other groups, marked a new level of sophistication. Instead of off-the-shelf chips, Makino and his colleagues started designing their own custom integrated circuits, putting one entire pipeline on a chip and arranging 48 chips in parallel. They took an even bigger step with GRAPE-4, wiring up 1692 chips. Completed in mid-1995, it was the first computer in the world to break the Tflops barrier, with a peak speed of 1.08 Tflops. At the time, the fastest general-purpose supercomputer was a Fujitsu model with a peak speed of 280 gigaflops. GRAPE-5 was optimized for lower accuracy and power. But now GRAPE-6, built on a budget of about $4.2 million, once again wins the world's-fastest crown.

GRAPE power. Circuits hardwired for gravity thrive on complex simulations such as evolving a virtual moon.

Just as important for astrophysicists is the affordability. The most basic GRAPE-6 configuration, for about $13,000, has just four GRAPE-6 chips, each with six pipelines, and runs at 150 gigaflops. A single GRAPE-6 board sporting 32 chips and a total of 192 pipelines capable of 1 Tflops costs about $42,000. The full-sized GRAPE unveiled this week has 32 of those boards. That means that just about any group with even modest funding can put what Hut calls "a virtual astrophysical laboratory" on its desktop. As a result, "a bright new idea can be tested right away, as opposed to having to argue it in an application for supercomputer time in order to be able to try it out 6 to 12 months later," says Lia Athanassoula, a theorist at the Marseille Observatory in France, which has several different GRAPE configurations.

The enthusiasm of GRAPE users for their machines resembles that of early computer hackers. There are GRAPE users' conferences and even an occasional newsletter. "The community of GRAPE users is informal, but rather tight-knit," says Albert Bosma, who is also based at Marseille. "People help each other out with technical problems." The can-do spirit has paid off. By an informal and certainly incomplete tally, more than 40 journal papers published last year alone were based at least in part on GRAPE simulations.

GRAPE's tailor-made take on scientific computing might soon spread to other fields as well. Toshikazu Ebisuzaki, a GRAPE project veteran who now directs the Advanced Computing Center at RIKEN, the Institute for Physical and Chemical Research, near Tokyo, is modifying the GRAPE approach to tackle molecular dynamics. He says that just as computing gravitational attraction was a bottleneck for simulations of stellar dynamics, figuring Coulomb and van der Waals forces, which govern molecular attraction, is the bottleneck in simulating molecular dynamics. Ebisuzaki has already demonstrated the feasibility of modifying GRAPE chips to handle these calculations and is gearing up to start simulations of protein folding that may prove more practical and affordable than current approaches using supercomputers.

For Makino and his collaborators, claiming the prize as the world's fastest computer is nice, of course. But their primary interest is still astrophysics. High on their list of problems to tackle is just how black holes inevitably end up at the centers of galaxies, even in cases where two galaxies collide. There are various theories. But attempts to simulate them on previous GRAPEs proved maddeningly inconclusive. Makino thinks the ability of GRAPE-6 to handle more stars in greater detail may resolve the question. But it could be one of the problems that may just have to wait for GRAPE-7 or -8.

—DENNIS NORMILE

CREDIT: GRAPE