traveled to China this April to analyze them with Shu and other Chinese colleagues.

They found that the two fossils represented different species, and although the fossils measured only a couple of centimeters long, the researchers could recognize key vertebrate traits. They had rows of gills, and their muscles were arranged in W-shaped blocks along their flanks, a pattern unique to vertebrates. "They were presumably filter feeders, but they have these muscular bodies and things which we cautiously interpret as an eye," says Conway Morris. "And so presumably they could go along at a fair pace if they had to, and they might have grabbed prey."

The way we were. Artist's conception of ancestral vertebrate, about 2 centimeters long.

The researchers then tried to find a place for the fossils in vertebrate evolution. A number of researchers believe that vertebrates evolved from an ancestor something like *Amphioxus*, otherwise known as the lancelet. *Amphioxus*, which lacks eyes or fins and looks rather like a miniature anchovy fillet, has a notochord—a primitive backbone. The first vertebrates added new traits to that body plan, such as a skull with a brain; later vertebrates acquired jaws and fins. The most primitive vertebrate alive today is the hagfish, a jawless fish, and the second-most primitive is the lamprey.

Conway Morris and his colleagues concluded that the fossils fall into a surprisingly advanced position. One of the species, which the researchers named *Haikouichthys*, is most closely related to the lamprey. The other fossil—tortuously named *Myllokunmingia*—is more primitive (its gills are simpler), but Conway Morris says it is still a closer relative to us than to the hagfish.

Features seen on both fossils may help answer the controversial question of how early vertebrates evolved the paired fins that later gave rise to arms and legs (*Science*, 23 April, p. 575). The new fossils show what look like two long folds of tissue running along their underside—exactly what some theories of fin evolution predicted. "We think there's a reasonable case for a double arrangement," says Conway Morris.

Janvier, who has argued that the paired fins came much later, has his doubts. "From what I could see of the fossils, it's not 100% certain." He is also uncertain about the fossils' placement on the vertebrate family tree, because many details of the creatures' anatomy have been lost. He has no doubt that they are vertebrates, but says, "I wouldn't put my money on the exact positions."

If Conway Morris is right about the creatures' sophistication, however, millions of years of vertebrate evolution must have preceded them, reaching back before the Cambrian explosion. Some researchers already suspected as much, based on the clocklike divergence of genes in different animal lineages. According to a new study by Blair Hedges of Pennsylvania State University in University Park, for example, vertebrates got their start 750 million years ago. "Some of my colleagues who take molecular clocks seriously will be skipping for joy" over the new finds, Conway Morris acknowledges ruefully.

He himself doesn't think vertebrates got their start so long ago. He suspects the first ones arose just before the Cambrian Period, about 565 million years ago. The traces of these ancestral creatures, he thinks, may be waiting, still unrecognized, among the fossils known as the Ediacaran fauna. "These stem groups are all lurking down there," Conway Morris maintains, "but we're just too dim to see them."

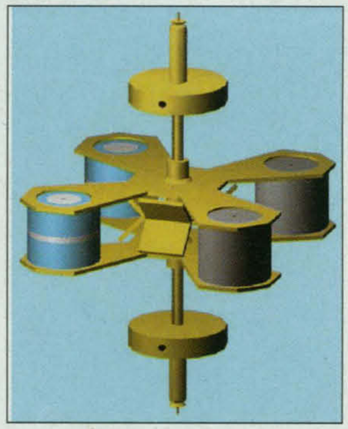
–CARL ZIMMER

Carl Zimmer is the author of the book *At the Water's Edge*.

PHYSICS

Gravity's Gravity Vindicates Einstein

Between them, general relativity and quantum theory explain all of nature's forces, and yet they refuse to be married. The strong and weak nuclear forces and electromagnetism are all described by quantum theories that mesh in a very satisfactory way. On the other hand, general relativity—Einstein's theory linking the force of gravity to the geometry of space and time—steadfastly refuses to be seduced into the quantum fold. "A goal in physics is to unify all the forces, that is, to combine gravity with the other three in one grand theory," says Blayne Heckel of the University of Washington, Seattle.



Earth (and moon) in the balance. Toy celestial bodies rest on a torsion balance, designed to detect differences in their response to the sun's gravity.

Like so many others, Heckel, Eric Adelberger, and their Seattle colleagues don't know how nature might entice the two parties to walk together down the aisle. So the Seattle group has instead looked for the possible progeny of such a match. One such child would be a difference in the way gravity acts on mass and on gravitational energy itself. But this hypothetical love child, expected in some scenarios of a deep connection between gravity and the quantum world, is nowhere to be found, the group determined.

Einstein built his theory of general relativity on the premise that gravity acts equally on all forms of mass-energy. Experimenters have shown that nuclear binding energy and energies due to electromagnetic interactions do indeed obey this "equivalence principle." For example, a proton and a neutron combine to make an object with less mass than the component parts; the binding energy holding the two parts together accounts for the missing mass. Yet experiments show that the combination and the individual parts free-fall at the same rate in a gravitational field.

But no one has yet shown that gravitational energy responds to the pull of gravity in the same way as all other forms of mass-energy do. Some theories—including string theory, the current favorite in the attempts to synthesize a quantum theory of gravity—suggest it might not. "Many theorists expect that at some point we will find a difference," says Heckel.

Lab experiments can't study the impact of gravitational binding energy, since the energy tied up in the mutual pull of fragments of lab-sized objects is minuscule. The place to look, Kenneth Nordtvedt of Montana State University suggested more than a decade ago, is in the tug of the sun on the moon and Earth. Although Earth's gravitational binding energy is small—a mere half a microgram per kilogram—because Earth is big, around 3 trillion tons of its mass is transformed into pure gravitational energy. The moon's gravitational binding energy is around 2000 times smaller, but still big enough to displace the center of the moon's orbit relative to Earth if the sun's gravity treats mass and gravitational binding energy differently.

Spotting these effects means monitoring the Earth-moon distance to high accuracy. By using lunar laser ranging, in which a laser beam bounces off reflectors dropped off on the moon by astronauts, Nordtvedt and others tracked this separation to centimeter accuracy and found, within the limits of the experiments, that the Earth and moon do indeed fall towards the sun at the same rate.

Nordtvedt himself pointed out a loophole, however: Some quantum gravity theories suggest gravity might act differently on the Earth and moon because of compositional differences such as Earth's

CREDITS: (TOP TO BOTTOM) ILLUSTRATION BY JOHN SIBBICK; S. BAESSLER *ET AL. PHYSICAL REVIEW LETTERS* iron-dominated core, explains Heckel. "So one wants to know that the Earth and moon don't fall at different rates due to composition differences, and by an amount which could cancel a gravitational self-energy effect," adds Nordtvedt. Such a cancellation is "quite unlikely," but the Seattle group has sought to resolve this potential ambiguity.

The Seattle experiment, reported in this week's *Physical Review Letters*, consists of a torsion balance: a fine wire supporting a tray that can rotate by twisting the wire. On the tray are four weights, alternating toy Earths and moons, all weighing exactly 10 grams. The two Earth-like weights are made of steel to simulate Earth's core material, while the two moon-like weights are made of quartz and magnesium-based materials that simulate both the Earth's and the moon's mantle material. The whole experiment is rotated so that the "planets" turn past the sun in 40-minute-long "days." Any gravitational preference of the sun for the toy moon or toy Earth should yield a twist in the torsion balance. "It's a very clever idea, making these little models for the planets," says Clifford Will at Washington University, St. Louis. The experimenters have produced "extraordinarily precise measurements."

The team found no twist. Their results, combined with the laser ranging, show that "gravitational binding energy falls at the same rate as all other forms of mass-energy to better than a part per thousand," says Heckel. Heckel declares himself unsurprised at the result, and Einstein's theory triumphs yet again.

Yet there's some comfort for the string theorists too, says Will, because differences in the rates of fall of different bodies could lie beyond the sensitivity of current experiments. "We really think there's a chance of finding a violation at some level," Will says. So the dating game continues, but gravity remains as aloof and celibate as ever.

—ANDREW WATSON

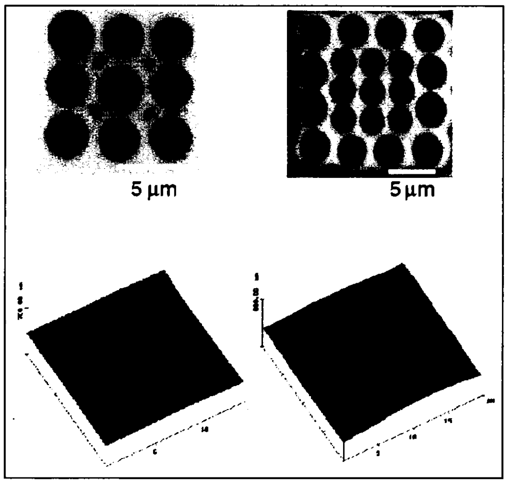
Andrew Watson is a science writer in Norwich, U.K.

NANOTECHNOLOGY

Patterning Plastic With Plentiful Pillars

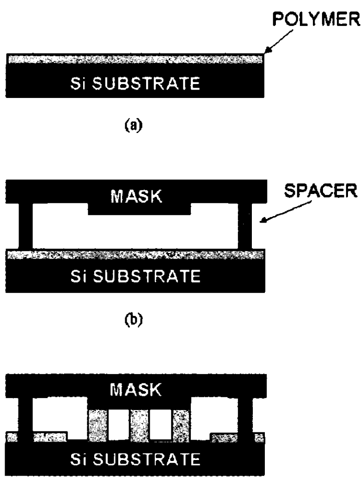
RICHMOND, VIRGINIA—Rome wasn't built in a day, but a nanosized version of it may be in the near future. At the International Symposium on Cluster and Nanostructure Interfaces here last week, Stephen Chou, an electrical engineer from Princeton University in New Jersey, described a new microscopic patterning technique capable of creating arrays of plastic pillars, each less than a thousandth of a millimeter across, that resemble nothing so much as tiny versions of the great columns of Rome's coliseum. Cheap, fast, and versatile, the patterning scheme could help create novel plastic displays and electronic devices. The pillars themselves could not only be used as wires in plastic electronics, but could also direct the growth of other materials, such as metals and semiconductors, into regular patterns.

"It's very beautiful work," says Peru Jena, a physicist at the Virginia Commonwealth University in Richmond. It's the beauty of simplicity, says Jena, because the technique requires nothing more than putting a mask above a heated thin polymer film and waiting a few minutes while the pillars assemble themselves. Chou says that, at around 500 nanometers in diameter, the pillars are now more than twice as large as the finest features that photolithography—the workhorse patterning technology of the chip industry—can lay down on silicon. Nevertheless, K. V. Rao, a physicist at the Royal Institute of Technology in Stockholm, Sweden, points out that photolithography has been refined over decades. As for the new technique, "this is just the beginning," he says.



All rise. Polymer pillars rise from a flat molten polymer layer toward an adjacent mask.

It was an unexpected beginning, Chou says. He and his students were working on a related patterning technique in which they imprint a pattern of nano-sized ridges and grooves on a soft polymer with a tiny embossing stamp. In one experiment, however, tiny dust grains, each about 0.5 micrometers high, strayed onto the polymer before the stamp was applied. Like tiny boulders, the dust grains prevented the stamp from pushing into the polymer and making an impression. Yet when the Princeton researchers removed the stamp and looked at the surface of the film, they still saw a pattern of dots that matched features on the stamp. The stamp had somehow elicited a pattern without ever touching the surface.



Self-made. Electrical attractions caused pillars to take shape.

Surprised, they repeated the experiment to see if they could find out what had happened. They created another set of masks, this time incorporating tiny posts that held them about half a micrometer above the polymer surface, and again they saw the array of dots. Those dots turned out to be tiny polymer pillars that had grown up from the surface of the plastic layer to the mask.

"We still can't be sure" what causes the pillars to form, Chou says. He and his colleagues have determined that a polymer film produces pillars only when it is heated enough to melt and the masking material above is electrically conductive, which leads Chou to speculate that the interplay of electrical charges in the mask and the polymer film creates the pillars. Localized concentrations of charge in the mask likely induce an opposite charge in the nearby film, he says, generating electrostatic forces that pull the pliable polymer upward.

If correct, says Chou, this explanation suggests that the pillars should form first at the corners of the mask, since charges preferentially bunch there. And when the Princeton team set up a video camera to watch their pillars grow, they found that pillars formed first at the corners and edges of the film below the mask and slowly worked their way in toward the center.

So far, Chou and his colleagues have made most of their pillars in a polymer called polymethylmethacrylate, more commonly known as plexiglass. But the technique also works with conducting polymers, which could serve as the basis of futuristic flat panel displays and disposable electronics. To test whether their pillars could make conductive wires for such devices, Chou and his colleagues laid down a film of conducting polymer on a metal strip and then grew pillars upward to touch another metal strip passing over the first at right angles. The group hasn't tested the electrical behavior of the pillars, but Chou says he fully expects that they will provide conductive pathways between the metal conductors. If so, plastic pillars may be in for a rising future.

—ROBERT F. SERVICE

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