COMPUTER MODELS

Paleontologists Learn to Shake Up Virtual Bones

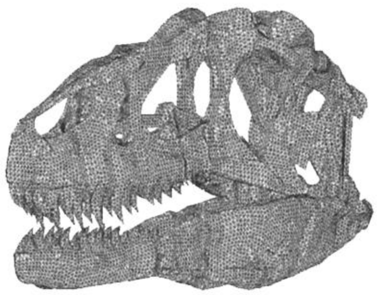
A sophisticated engineering tool is providing insights into how fossil skulls and other bones worked in real life

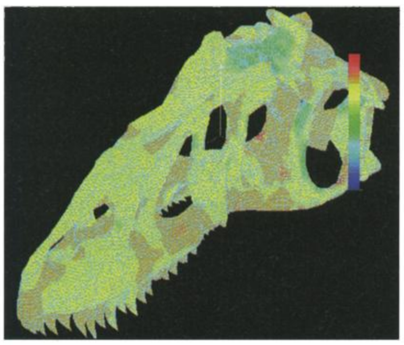
In their dreams, some paleontologists wire strain gauges to the skulls of extinct killers and ram the skulls into chunks of meat to simulate a deadly attack. Understanding the stresses on the skulls might help clarify the ecology and evolution of predators. But fossil skulls are too rare to be sacrificed and are now made of rock, not living bone. Thanks to computing power and some engineering savvy, however, paleontologists have a safer way to turn their most precious fossils into crash-test dummies.

The technique is called finite-element analysis. Engineers have used it for decades to investigate forces on an object, be it a bridge or a booster rocket. They recreate the structure with a mesh of small, linked polygons, then designate its elasticity and other material properties at each tiny site. Force is applied, and as each element nudges its neighbors, the computer solves simultaneous equations to calculate the compression and tension. By making a finite-element model and loading it in various ways, engineers can study how a structure might fail and use those insights to optimize its design. In the late 1970s, biomedical researchers began to use the technique to study, among other things, the biomechanics of bone and the strength of tooth implants.

More recently, some biologists and paleontologists have begun to tackle questions about animal mechanics, such as the strength of horse hooves—and test ideas about anatomy, evolution, and ecology. In this week's issue of *Nature*, a theory about the hunting strategy of a dinosaur is backed up by a finite-element model of a fossil with unprecedented detail. "In the past, people just waved their arms" when talking about the biomechanics of ancient creatures, says Don Henderson, a functional morphologist and postdoc at the Johns Hopkins University School of Medicine who works on computer modeling in paleontology. "Now you can actually make it rigorous."

The first major effort to examine fossils using finite-element analysis began at Cambridge University in the United Kingdom. Paleontologist David Norman and his graduate student, Ian Jenkins, heard about the technique in 1997 from Jeff Thomason, a biologist at the University of Guelph in Ontario, Canada, who was presenting findings about the evolution of the mammalian hard palate. Jenkins went on to use the technique to study a group of saber-toothed reptiles, called gorgonopsids, that were among the first carnivores on land. The abundant gorgonopsid had apparently outcompeted other saber-toothed predators of the time, such as the therocephalians. Jenkins hoped to find their competitive advantage in some subtle feature of their skulls.





Number crunching. Based on a CT scan *(top)*, a finite-element model shows how an *Allosaurus*'s skull is squeezed.

CREDITS: (TOP) E. RAYFIELD/MUSEUM OF THE ROCKIES; (MIDDLE AND BOTTOM) E. RAYFIELD

To test his hypothesis, Jenkins made a simplified computer model of the gorgonopsid skull. Using data from dogs, he subjected the virtual skull to forces involved in attacking prey. The strain was concentrated along numerous sutures in the palate that acted like shock absorbers. These and other features would have absorbed the shock from the blow inflicted by their powerful jaws.

Other saber-toothed reptiles sported similar peculiar sutures, it turned out, but theirs were less pronounced. Evidently, gorgonopsids were built to bite harder. "When that came out, I was hugely pleased," Jenkins says, because it suggested a reason for their success: a wider diet that allowed them to better adapt to changes in the faunas during the late Permian, some 250 million years ago. Now a postdoc at the University of Bristol, U.K., Jenkins is using finite-element models to examine what filled the niche when gorgonopsids went extinct at the end of the Permian.

Jenkins's simplified models only scratched the surface of the finite-element method. Emily Rayfield, a graduate student at Cambridge, is working on a virtual skull with nearly 250,000 elements. Her subject is a remarkably complete *Allosaurus* found in Wyoming in 1991 and dubbed "Big Al." Like the skulls of many other theropod dinosaurs, an *Allosaurus* skull is a lattice of small, thin bones that looks both light and strong. Rayfield wants to understand how its 80-centimeter-long skull functioned as a tool and a weapon.

To estimate how much force Big Al's jaw muscles would have exerted, Rayfield examined muscle scars on the bones and compared them with scars and muscles on living dinosaur relatives, such as birds and crocodiles. Then she reconstructed the muscles in clay on a cast of the skull. The strength of a muscle depends on its cross-sectional area and on the metabolic rate of the animal that flexes it. Rayfield measured the thickness of the clay muscles and, to be on the safe side, calculated muscle strength for a range of metabolisms, guessing that the true value lay somewhere in the middle. She found that *Allosaurus*'s jaws were only a fourth as powerful as those of a modern alligator. "I was really surprised that it had such a weak bite," Rayfield says. She infers that *Allosaurus* didn't crunch with the kind of bone-splitting bites that the thicker headed *Tyrannosaurus rex* seems to have used to dismember carcasses.

Rayfield then used her finite-element model to test the strength of Big Al's skull. By applying force through six teeth in the virtual head, she found that the upper jaw and the rest of the skull could have withstood a load of up to 6 metric tons—26 times the maximum force from clenched teeth, Rayfield and colleagues report in the 22 February issue of *Nature*.

Why such drastic overengineering? Rayfield suspects that the skull had to absorb such large forces when *Allosaurus* collided with its prey. She imagines *Allosaurus* running into a fleeing victim with jaws agape, slamming its upper teeth in like a hatchet and then using its strong neck muscles to rake out flesh with its teeth. "At first glance, it seems like it would be a weird approach to biting," says Tom Holtz of the University of Maryland, College Park. But it fits with the observation, published last year, that *Allosaurus* could open its jaws extremely wide. "It's appealing to see that the mechanical analysis is consistent," he says.

Such consensus is reassuring, because paleontological modeling is far from an exact science. The material properties of fossil bones and the applied forces are all estimates, and figuring out muscle strength is just part of modeling a complicated motion. As a result, paleontologists say they are on guard against the "garbage in, garbage out" effect. "I wanted solid answers," recalls Michael Fastnacht, a doctoral student at Johannes Gutenberg University in Mainz, Germany. "But when I went to the engineers, they said, 'Oh, no, even we don't get those.' " What's more, there's rarely a way to test a theory short of building a scale model of a dinosaur skull out of modern bone.

Still, for all the caveats, Fastnacht and colleagues are pressing ahead with plans to investigate the bony crests that grace the tops of some pterosaur skulls. The crests have been proposed as rudders for flying or buttresses to strengthen the snout during a bite. Other paleontologists talk about modeling foot bones of dinosaurs, and paleoanthropologists are interested in using the technique to study chewing and hip function in primates. It's not *Jurassic Park*, they acknowledge, but detailed answers from this high-tech approach may help bring these old bones to life. —**ERIK STOKSTAD**

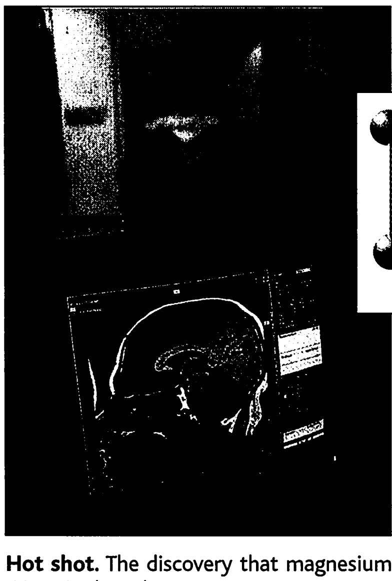
SUPERCONDUCTIVITY

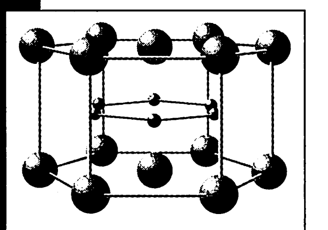
Material Sets Record for Metal Compounds

Magnesium diboride, one of the simplest compounds around, superconducts at nearly twice the temperature of its closest metallic rival

The discovery of ceramic superconductors in 1986 lit a fire under physicists worldwide. Experimentalists stayed up for nights on end concocting new ceramic mixtures and testing the results. Theorists jumped at the latest data and racked their brains trying to explain how the newfound ceramics could conduct electricity without any losses at temperatures far above those of the conventional metallic variety. Physics meetings took on the aura of jam-packed rock concerts. Now a new discovery, although clearly more modest, has the superconductivity community abuzz again.

At a meeting last month in Japan,* researchers led by physicist Jun Akimitsu of Aoyama Gakuin University in Tokyo announced that they had discovered a boron-containing metal compound that superconducts at 39 K, nearly twice the temperature of the previous metallic record holder. Although some ceramics can superconduct at temperatures up to 96 degrees higher, most metallic compounds are better at carrying current across gaps between grains of material and thus make better wires.





Hot shot. The discovery that magnesium diboride *(inset)* is a superconductor could mean more powerful, less costly magnets in MRI machines.

CREDITS: (LEFT) OWEN FRANKEN/CORBIS; (INSET) CAMERON SLAYDEN

"This is the highest observed [superconducting temperature] of any intermetallic compound," says Paul Canfield, a physicist at Iowa State University in Ames, and the Department of Energy's Ames Laboratory. "That's a big hairy deal."

Researchers have spent decades looking at boron-containing compounds for hints of superconductivity, because theory suggests that boron's light weight should give any compound it is in a relatively high superconducting temperature. Yet somehow they overlooked one of the simplest compounds around, magnesium diboride (MgB_2), a tan powder that can be purchased from standard laboratory chemical suppliers. "I'm really amazed that they didn't find it before," says Jorge Hirsch, a superconductivity theorist at the University of California, San Diego. "It's like putting cinnamon in your magnetometer and finding it superconducts," marvels Canfield.

In an e-mail exchange, Akimitsu declined to provide details of his team's discovery or explain why they decided to look at MgB_2, because the team currently has a paper on the subject under review. In any case, the result has already been replicated by other teams in Japan, the United States, and the United Kingdom. Now physicists are racing to make sense out of MgB_2's abnormally high superconducting temperature.

Materials superconduct when electrons inside overcome their usual repulsion and pair up, with electrons effectively taking on the size of the paired structure. That property allows them to surf through a material's crystalline lattice without banging into atoms that would slow their progress.

According to the "BCS" theory of superconductivity, first outlined in 1957 by John Bardeen, Leon Cooper, and Robert Schrieffer, this pairing occurs in metallic superconductors as a result of a kind of electronic water skiing: The movement of one electron creates vibrations in the surrounding atomic lattice that then sweep another electron along in its wake. But this link between electrons normally breaks when the temperature rises much above 20 K. The heat produces extra vibrations that act like rogue waves sending the trailing electron skiers careering in all directions.

In high-temperature ceramic superconductors, electron pairing is widely thought to be due to the magnetic behavior of atoms in the material, although this remains in dispute. So figuring out what is keeping electron pairs together at nearly 40 K in the nonceramic MgB_2 has become the latest contest in the most competitive area of materials physics. "Tally ho," says Canfield. "The chase is on." Adds Hirsch: "I can't sleep. It's extremely exciting."

Hirsch's insomnia may be brief, however. A series of early reports suggests that MgB_2 is most likely a BCS superconductor, albeit a very good one. In one paper posted to the Los Alamos physics preprint server on 3 February and accepted for publication at *Physical Re-*

* Symposium on Transition Metal Oxides, 10 January, Sendai, Japan.