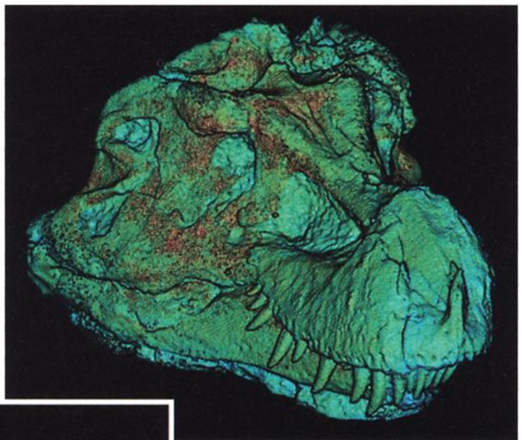
PALEONTOLOGY

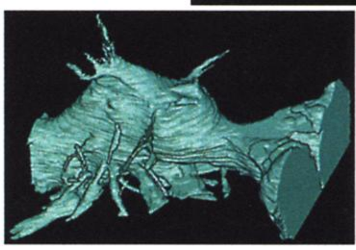
Learning to Dissect Dinosaurs—Digitally

Technology borrowed from medicine and industry helps paleontologists peer into specimens with x-ray eyes

Chris Brochu's mission was to get inside the head of the most expensive dinosaur on Earth. Brochu, a paleontologist at The Field Museum in Chicago, was hired to describe the complete anatomy of Sue, an $8.4 million *Tyrannosaurus rex*—including the hidden cavities of the brain. As with any precious specimen, cracking open the skull was clearly out of the question. Instead, Brochu and his colleagues shipped the 1-ton skull to Rocketdyne, a division of Boeing in Chatsworth, California, which put Sue in a computed tomography (CT) scanner designed to find microscopic flaws in rocket engines.

As the skull slowly rotated, x-rays penetrated and created salami-like cross sections. Back at The Field Museum, Brochu digitally manipulated the scanned images to produce a virtual cast of Sue's braincase that revealed olfactory bulbs the size of grapefruits. The result, Brochu reported in the March issue of the *Journal of Vertebrate Paleontology,* bolsters the idea that the enormous predator had a well-developed sense of smell.





Brain scan. CT scan reveals Sue's 30-cm-long brain without damaging her 1.7-meter-long skull.

Physicians routinely use CT scanning to diagnose brain tumors and other life-threatening conditions. But in the past 2 decades, as the images have grown sharper, paleontologists have increasingly trained the technique on long-dead animals as well. CT cross sections offer an inside view of rich anatomical detail, including everything from bony canals that once held nerves to the internal networks of dinosaur noses. Off-the-shelf software allows any scientist to view the slices, while more sophisticated and expensive programs generate a three-dimensional (3D) replica of a fossil. The resulting virtual specimen can help preparators chisel a fossil from its matrix without destroying any bone and can reveal features that even the most delicate preparation could never uncover. And digital data, unlike priceless specimens, can be easily and cheaply transported to colleagues. CT scanning is "a very important tool for paleontology," says Jack Horner, a dinosaur expert at the Museum of the Rockies in Bozeman, Montana.

To be sure, the technique won't work on all samples. And the images still require a trained eye to interpret. Still, CT scanning has contributed to a number of high-profile discoveries, the latest of which may be a four-chambered dinosaur heart (*Science*, 21 April, p. 416). For some paleontologists, using the tool can be as much fun as being in the field. "It's a very exciting feeling, like when you're excavating a fossil," says Larry Witmer of Ohio University College of Osteopathic Medicine in Athens. "When you look inside the brain cavity of a dinosaur skull encased in rock, you are the first person to look inside its head."

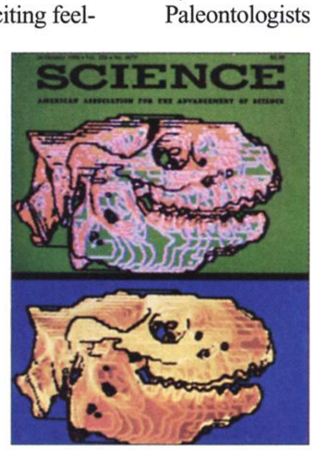
Inside view

One of the first scientists to experience that thrill was Glenn Conroy, an anthropologist who was then at Brown University. In 1983, while waiting in a supermarket check-out line, he saw a magazine cover with a computer-generated image of a human face. Craniofacial surgeons were using the then-novel technique—producing 3D images from CT scan digital data—to help reconstruct the face and skull of a 4-month-old girl with a birth defect. "I was amazed that you could electronically dissect a living child's face," Conroy recalls. "It gave me the idea that maybe we could do this with fossils."

Conroy teamed up with the doctors who had scanned the child's head, a group at Washington University School of Medicine in St. Louis, where Conroy now works. They tried out the CT scanner on a common fossil ungulate called an oreodont. The cranium was filled with sandstone, which Conroy hoped the CT scan could distinguish from the fossil bone.

Standard medical x-rays aren't always sensitive enough to show the contrast between bone and rock, and they make 3D objects such as skulls difficult to interpret. "When you put something in an x-ray machine, you're looking at everything at once," Horner says. "It's hard to tell what's on top, what's on the bottom, and what's in the middle." In computed tomography, however, the x-ray source rotates around a specimen, probing one cross-sectional region at a time with a fan-shaped beam. Sensors measure the beam's attenuation, which varies with density. The result, Conroy found, was a 3D image that neatly distinguished between fossilized bone and the rock matrix. "It worked beautifully, given the primitive state of scanners," he says.

Even so, several stumbling blocks remained. Medical scans were designed to be viewed on a monitor or film, not downloaded to a computer. Moreover, early scans were grainy—about on par with early Pac-Man video games. "It was almost a joke," says Jim Clark, a paleontologist at George Washington University in Washington, D.C. Eventually, the images became good enough for clinicians, but still not sharp or powerful enough for paleontologists to study small, finely detailed fossils.



Sharper image. Resolution has come a long way since 1984.

Paleontologists turned to industrial scanners, which are designed to probe important mechanical parts for flaws. These machines yielded better resolution and thinner slices; so-called micro-CT scanners can now obtain slices down to 10 micrometers. In 1993, Tim Rowe, a paleontologist at the University of Texas, Austin, showcased the technology on a rare and fragile 3.8-centimeter-long skull of *Thrinaxodon liorhinus*,

CREDITS: C. BROCHU/THE FIELD MUSEUM

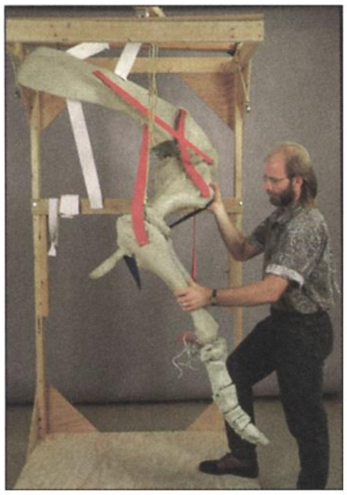
Fossils Made to Order, Any Size

Large dinosaur bones are "damn cumbersome," grumps Rolf Johnson, a paleontologist at the Milwaukee Public Museum. To figure out the posture and gait of ceratopsian dinosaurs, Johnson must examine the way their limbs articulate. But that's tough to do when a single meter-long shoulderblade can weigh as much as a bag of cement. In the early 1990s, Johnson discovered a partial solution by making fiberglass casts of *Torosaurus* shoulder, leg, and foot bones, inserting universal joints, and rigging them with rubber bands in a 2-meter-tall wooden gantry. It worked well—except when Johnson had to wrestle the contraption into his pickup truck and drive it to meetings.

Today, thanks to industrial scanning and rapid prototyping, Johnson has it easy. His 1:6 scale replica of a *Triceratops* forelimb fits in a briefcase. The technology, normally used to make mock-ups ranging from juice squeezers to engine parts, can reproduce a fossil and change its scale in the process. A few massive dinosaur bones have already been shrunk to a more manageable size, and in principle tiny bones could just as easily be enlarged. What's more, the right-sized replicas can be mailed to collaborators at a reasonable price—try shipping an 8-meter-long *Triceratops*—and then stored on a shelf.

One of the first attempts to scale down a fossil came in 1998, when Jeff Wilson, a graduate student at the University of Michigan, Ann Arbor, teamed up with Arthur Andersen of Virtual Surfaces Inc. in Mount Prospect, Illinois, a company that edits digital versions of industrial parts. They converted a meter-long, 115-kilogram humerus of a sauropod into a version that was just 12 centimeters long, yet completely realistic to the eye. "Basically everything you could see on the sauropod, you could see on the small bone," says Hans Larsson, a graduate student at the University of Chicago. "Now you can store a 60-foot [18-meter] sauropod in a filing cabinet."

Johnson's miniature dinosaur originated with the Smithsonian Institution's 1998 decision to disassemble its *Triceratops*, on display since 1905 and badly in need of conservation. While the bones were accessible, Ralph Chapman, a paleontologist and morphometrician at the Smithsonian's National Museum of Natural History in Washington, D.C., decided to create a digital replica. He struck up a collaboration with Andersen and Lisa Federici of Scansite, a company in Woodacre, California. Once they had a digital rendition, Federici persuaded toy manufacturer Hasbro to create a scaled-down physical model in its Cincinnati facility. The technique, called stereolithography, uses a laser to cure light-sensitive resin. Layer by layer, the tiny *Triceratops* bones rose from a vat of liquid resin.



More legroom. Rolf Johnson comes to grips with a life-sized *Torosaurus* forelimb.

The model is much more than a plaything, and it provides unique insights into the specimen and the ancient animal's physiology. While examining the *Triceratops* bones with Chapman, Johnson realized that the front shoulder blade seemed too small for the end of the humerus. The error occurred because the skeleton is a composite, assembled from at least 10 individuals. And the mismatched joint might have prevented the paleontologists from knowing the true extent of limb motion. "I don't think I would have noticed that with the real fossils, because we couldn't put them together and move them," Johnson says.

Another insight came during a visit to the Smithsonian by Kent Stevens, a paleontologist and computer scientist at Oregon State University in Corvallis. To make the elbow more realistic, Stevens and Chapman cut up a computer mouse pad and added it as faux cartilage. When they rotated the ulna, the pair noticed that *Triceratops*'s elbow could have locked in place. Hoofed animals such as cows and horses lock their limbs in a similar way to sleep standing up. *Triceratops* may have snoozed while upright too, or it might have braced itself while locking horns. "We would never have gotten into that idea if we had been solely looking at 3D software," Stevens says.

Subcompact. A model of a *Triceratops* skeleton can now be made in a handy yet accurate tabletop version, as Kent Stevens demonstrates.

Both Stevens and Johnson say that handling the bones provides a crucial reality check for computer models of locomotion. "I'm suspicious of only scanning the bones and playing with them in the computer," Johnson says. "You can make the computer do things that may look realistic but in fact are not biomechanically reasonable." Prototyping makes it possible to constrain speculation about the awkwardly heavy bones of large beasts.

The technique also lets paleontologists touch parts of a fossil that would otherwise be inaccessible without sawing. In 1995, Larsson and Andersen created a cast of the braincase of a predatory dinosaur called *Carcharodontosaurus*. After scanning the 1.6-meter-long skull by computed tomography (CT), they used a prototyping technique that lays down sheets of paper and glue, then trims them to size with a laser.

Right now the technique is probably too expensive for most paleontologists. A resin prototype of a 10-centimeter-long bone goes for about $1000, Andersen says, while Chapman's pro bono *Triceratops* would have cost upward of $200,000. "Rapid prototyping is something we're all waiting for," says Mark Norell, a paleontologist at the American Museum of Natural History in New York City. He's optimistic that the technology will become much cheaper and provide even higher resolution.

Indeed, prototypes consisting of cornstarch and sugar are already being made at a cost of about a dollar per cubic inch. And desktop prototyping machines that resemble inkjet printers are on the horizon. Soon, instead of shipping bones by mail, paleontologists might simply FTP data from a CT scan and have their colleagues print out 3D replicas.

–E.S.

CREDITS: (TOP TO BOTTOM) R. CHAPMAN/APPLIED MORPHOMETRICS LABORATORY, NATIONAL MUSEUM OF NATURAL HISTORY

Open wide. Unerupted teeth appear in a CT cross section of a *Diplodocus* skull filled with rock.

a 240-million-year-old relative of early mammals. He had struck up a collaboration with Scientific Measurement Systems, an Austin-based company that builds scanners with a resolution two orders of magnitude higher than that of most medical scanners. "The first slices that came out made my eyes bug out," Rowe recalls. The result was a CD-ROM that many paleontologists consider a landmark digital monograph.

Another advantage of industrial scanners is that they can handle fossils much bigger than the human body. In 1992, Horner and his team loaded up all of his museum's dinosaur skulls—including ones that wouldn't fit into a medical scanner—and drove them to Cincinnati in a U-Haul truck. There they CT-scanned the fossils at a facility where the General Electric company examines jet engines. Horner now has two UNIX computers crammed with CT scans from some three dozen dinosaurs.

Paleontologists such as Horner scrutinize CT images for traces of long-vanished physiology. Ohio's Witmer, for example, found extensive networks of capillaries in the nasal cavity of several dinosaurs that may have helped cool the brain (*Science*, 5 November 1999, p. 1071). Tiny tracks of long-gone blood vessels "can be difficult to sort out in CT scans, yet that's the only way to get the information," he says. A CT scan through the snout of the giant sauropod *Diplodocus* revealed rows of teeth ready to emerge—something that had never been seen before.

Such glimpses of biological infrastructure help paleontologists identify new, measurable characteristics that they can use in sorting out evolutionary connections among creatures. Skulls, with their innumerable recesses and canals that conduct nerves and blood vessels, are particularly rich sources of evolutionary information.

The ease of transmitting CT data will also make important, often inaccessible, specimens widely available. Scanning programs are already under way in various countries. Fred Spoor, an anthropologist at University College London, is now working with the National Museums of Kenya in Nairobi to help scan their fossils. The images will serve as an archive and as easily transferred digital "casts" of the specimens. Washington University's Conroy and Horst Seidler of the University of Vienna have similar collaborations in Tanzania, Ethiopia, and South Africa.

In the United States, one center of paleontological CT is at the University of Texas, Austin. In 1997, Rowe and colleagues William Carlson and John Kappelman set up a state-of-the-art scanning lab. After securing $1.5 million in funding, Rowe and his team spent a year designing the specifications for two industrial scanners: a high-power source to probe objects as dense as meteorites, and a low-power source to examine fine detail.

Since the lab opened for business 3 years ago, more than 100 scientists have had their fossils probed and archived on CD-ROMs. Rowe's team provides advice on how to scan fossils and can turn the massive data files into a 3D image. Scanning prices begin at $104 an hour; and because the National Science Foundation helps support the facility, researchers with NSF grants get a 50% discount. Rowe says he has clients in the imaging lab about every week. Ultimately, Rowe would like to post on a Web site all of the several hundred specimens that have been scanned in the lab—although he promises to honor requests to wait until after publication.

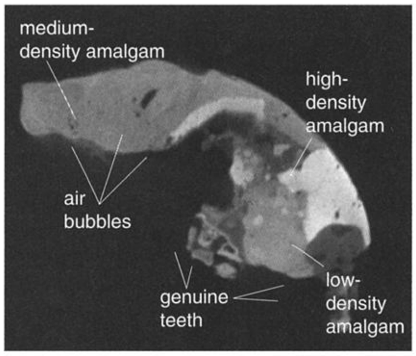
Digital dissection

For all its benefits, even its most ardent enthusiasts admit that paleontological CT scanning is not a magic wand. "There's a wide perception that you can feed a

CT Sleuthing Uncovers Fossil Misfits

Useful as they are for probing subtle features of fossil specimens, computed tomography (CT) scans are equally adept at singling out parts that *don't* belong. At the University of Texas's CT lab, Tim Rowe has identified mismatches that fooled even expert eyes.

Last July, artist Stephen Czerkas of The Dinosaur Museum in Blanding, Utah, brought the now-infamous *Archaeoraptor* fossil to Rowe's lab in Austin. Czerkas hoped to get valuable information about bones still encased in rock. Instead, much to his disappointment, the scanner revealed cracks suggesting that the body and tail of the fossil had come from different animals (*Science*, 14 April, p. 238). "It was a shock to see this," says Rowe, whose findings are being reviewed for publication.



Fake. CT slice showed that a primate skull is made of dental putty.

In January, a biologist who wishes to remain anonymous arrived with a small primate skull to be scanned. He had bought it from a fossil dealer for $2600, thinking it would make a good research specimen. After five CT slices, Rowe realized the entire skull was a clever fake carved out of dental amalgam, although it contained jaw fragments and some real teeth. The biologist was mortified, Rowe says. "He wouldn't even touch the specimen again."

Rowe notes that CT scanning could be a valuable tool for auction houses, museums, or anyone else interested in authenticating fossils. As in the case of the biologist, money as well as knowledge may be at stake. People who inadvertently donate bogus fossils to museums, for example, may see their tax deductions plummet. "I think there are going to be a lot of victims as these forensic techniques are put into play," Rowe says.

CT scanning can also reveal less fraudulent artistry. Early preparators of dinosaurs were highly skilled at reconstructing missing or damaged bone, but their anatomical interpretations can mislead present-day paleontologists if they remain undetected. "Very often the fakery—designed to make something look more presentable—is difficult to detect," says Larry Witmer of Ohio University College of Osteopathic Medicine in Athens. In the past, some fossil experts have missed the plaster and described it as bone. Adds Jack Horner, a paleontologist at the Museum of the Rockies in Bozeman, Montana, "CT scanning solves that problem." **–E.S.**

CREDITS: (TOP) L. WITMER/OHIO UNIVERSITY; (BOTTOM) T. ROWE/UNIVERSITY OF TEXAS, AUSTIN dinosaur skull into a CT scanner and all will be revealed," Witmer says. "It's not that simple." If a fossil is very dense or large, for example, x-rays have trouble passing through it and the signal may be quite noisy. The type of matrix matters, too; a calcium-rich bone encased in calcium carbonate–rich sediment may appear as nothing more than hazy shadows. As a result, trading the preparator's dental pick for the image processor's computer mouse may not mean a decrease in workload. Horner has spent years trying to decipher fuzzy images and decide where to draw boundaries between rock and bone.

Once the bone is located, the most challenging work has just begun. Witmer points out that physicians need years of training to read x-rays of human anatomy. Interpreting scans of extinct animals is far more difficult, especially if the specimens have been damaged after death or during fossilization.

All this means that interpreting CT images demands a tremendous amount of time. "You can make many images in an afternoon. Actually working on the images takes forever," notes Spoor, who uses CT scans to study details of hominid ear bones. "Ultimately, it will remain quite a specialized operation."

That's likely to remain true even as computers grow faster and software for image processing and data analysis ever more sophisticated. In the end, "it's not going to be the technology that provides the insight," Witmer cautions. "It comes down to humans who can understand the complicated and voluminous information that comes out of the scanner." –ERIK STOKSTAD

SOCIAL SCIENCE

Stress: The Invisible Hand in Eastern Europe's Death Rates

The end of communism opened up a life of economic uncertainty in the Eastern Bloc. And that, say scientists, may be exerting a deadly effect on residents

BUDAPEST—Soon after the former Eastern Bloc nations tossed off communist rule in the late 1980s and the Soviet Union imploded, people throughout Eastern Europe began dying in droves. Life expectancy plummeted. By 1994, for example, reaching the age of 57 was enough to put Russian men on the right side of the Bell curve. Even more frightening are the demographics: The groups experiencing the highest rates of premature death are young and middle-aged men. Traditional risk factors such as bad diet, smoking, excessive alcohol consumption, and infectious diseases all claim a share of the rising mortality in this part of the world, but they can't explain the growing disparity in life expectancy between East and West, researchers say. So what could be preying on a generation that should be in prime health?

On one level, the main culprit is clear: coronary heart disease. "What's killing them is diseases of the heart," says Gerdi Weidner, a psychologist at the State University of New York, Stony Brook. But Weidner's diagnosis—offered to a select group of 40 scientists from a range of disciplines at a NATO workshop convened here from 21 to 23 May to discuss Eastern Europe's epidemic of heart disease—wasn't based on physical symptoms alone. She and other presenters made the case that many Eastern Europeans may be dying from broken hearts. "The key words are 'giving up,' " says conference co-director Maria Kopp, a behavioral scientist at Semmelweis University in Budapest. When Eastern Europeans gained their freedom more than a decade ago, Kopp says, "people had very high expectations" that their lives would improve. For many, those hopes were dashed quickly by the bumpy transition to a market economy. Disillusionment led to stress and depression. And depression was a harbinger of death.

For gene jocks, that may be hard to swallow. "That social change can affect health is a fairly novel idea to a lot of biomedical scientists," says demographer Virginia Cain of the Office of Behavioral and Social Sciences Research at the U.S. National Institutes of Health (NIH). But for social scientists the hypothesis is in vogue. For instance, the European Science Foundation has just launched a 4-year project involving some 50 scientists to probe the link between psychology and mortality in Eastern Europe. Such a major research effort makes sense, says Cain: "The change to market economies provides a natural experiment to look at the impact of rapid social change on health."

Life Expectancy at Birth (in years) 1995–2000

	Women	Men	Difference
Russia	72.8	60.6	12.2
Estonia	74.5	63.0	11.5
Hungary	74.9	66.8	8.1
France	82.0	74.2	7.8
Germany	80.2	73.9	6.3
USA	80.1	73.4	6.7
Canada	81.8	76.1	5.7
Sweden	80.8	76.3	4.5
Cuba	78.0	74.2	3.8

Gender gap. In many Eastern European countries, a chasm in life expectancy has opened up between men and women.

SOURCE: WORLD POPULATION PROSPECTS: THE 1998 REVISION, UNITED NATIONS, 1999

Death behind the Iron Curtain. A gap in life expectancy between Eastern and Western Europe opened up more than half a century ago in the aftermath of World War II. "In Eastern Europe, you had a disastrous transition from one type of mortality to another, from infectious diseases to noncommunicable diseases," explains epidemiologist Martin Bobak of University College, London. Life expectancy stagnated in Eastern Europe until the late 1980s, apart from an uptick in the Soviet Union around 1985 in the wake of Mikhail Gorbachev's short-lived antialcohol campaign, says Vladimir Shkolnikov of the Center for Demography and Human Ecology in Moscow. In the meantime, Westerners, eating better and exercising more, were living longer with each passing year.

In 1989, Poland, Hungary, and Czechoslovakia all overthrew their oppressive communist regimes, and other Eastern European countries began following suit. Euphoria, however, soon gave way to uncertainty. People were in control of their own lives, but life was like walking a tightrope with no social safety net. Death rates skyrocketed and life expectancy plummeted, bottoming out about 6 years ago depending on the country. "The crisis goes along with the relative success of the transition to a capitalistic society," says Clyde Hertzman, an epidemiologist at the University of British Columbia in Canada. "Countries like Russia are relative basket cases."

Researchers seeking to unravel this trend discovered a multitude of causes. Smoking was the culprit in some countries, while poor diets—a lack of fruits and vegetables—led the way in others. Studies showed that the region's health care systems, while frayed, are not to blame for the life-expectancy gap, says Margareta Kristenson of Linköping Universi-