MAY ISSUE 1997

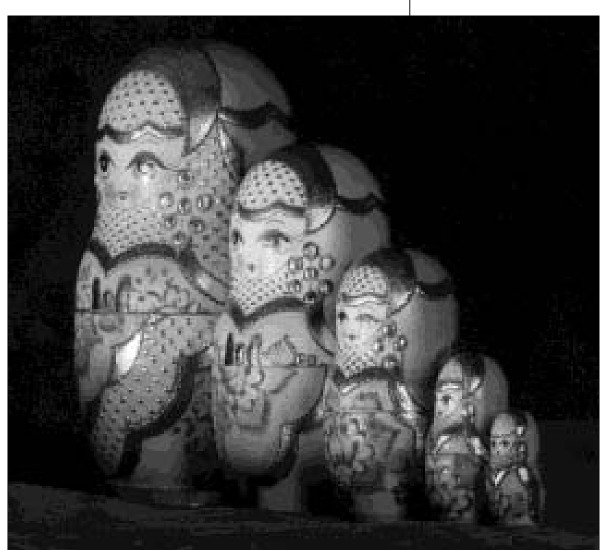
# DATELINE LOS ALAMOS

## THE TREE OF LIFE

### SCIENTISTS MODEL NATURE'S SYSTEM OF FRACTAL BRANCHING NETWORKS

The words "drawn to scale" are familiar to non-scientists and scientists alike and their meaning is easily understood: that the proportions of the original structure are preserved in the artist's scaled-down representation.

Scientists have observed for more than 50 years that nature also preserves proportions in adapting biological features from species to species. Cardiovascular systems, respiratory systems, plant vascular systems, and insect tracheal tubes all exhibit the same continuously branching structure that increases or decreases in scale as a quarter power of body size.



➔ Fractals are structures that exhibit self-similarity — the smallest fraction of the thing looks exactly like the whole thing. Russian nested dolls are man-made fractals. In nature, fractals are found in a remarkable number of things, including snowflakes, trees, river systems, and the human cardiovascular system.

Recently published research by a Los Alamos researcher and his colleagues at the University of New Mexico for the first time presents a general model that explains the origin and prevalence in nature of "quarter-power scaling."

> "Cardiovascular systems, respiratory systems, plant vascular systems, and insect tracheal tubes all exhibit the same continuously branching structure that increases or decreases in scale as a quarter power of body size."

The model is the brainchild of Los Alamos physicist Geoffrey West and University of New Mexico biologists Jim Brown and Brian Enquist, who two years ago began a collaboration under the auspices of the Santa Fe Institute to study these universal scaling laws. The collaborators were brought together by Mike Simmons, former vice president of the Santa Fe Institute and now an extended faculty member living in Washington, D.C., who knew of their respective professional backgrounds and their shared interest in scaling laws. The researchers met and immediately clicked, both professionally and personally.

"We came to the same problem from very different angles," West said. At Los Alamos, West was applying his high-energy physics background to the mystery of why all animals regardless of their body size obey the same simple scaling law for metabolic rate. The answer, he believed, was essential to understanding how evolution maximizes fitness.

"Metabolic rate — how much energy an organism consumes per second to maintain life — is proportional to body mass to the three-fourths

DATELINE LOS ALAMOS

A MONTHLY PUBLICATION OF THE PUBLIC AFFAIRS OFFICE OF LOS ALAMOS NATIONAL LABORATORY

LOS ALAMOS NATIONAL LABORATORY, AN AFFIRMATIVE ACTION / EQUAL OPPORTUNITY EMPLOYER, IS OPERATED BY THE UNIVERSITY OF CALIFORNIA FOR THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT NO. W-7405-ENG-36

*EDITOR*
Diane Banegas

*MANAGING EDITOR*
Meredith Coonley
(505) 665-3982 • suki@lanl.gov

*STAFF WRITER*
Theresa Salazar

*CONTRIBUTING WRITERS*
Kathy DeLucas • James Rickman

*CONTRIBUTING PHOTOGRAPHER*
LeRoy N. Sanchez

*CONTRIBUTING ILLUSTRATORS*
Trudy Filer • Zizi Kolshorn
Donald Montoya • Gloria Sharp

*PRINTING COORDINATORS*
G.D. Archuleta • Sandra Lopez

LOS ALAMOS NATIONAL LABORATORY
PUBLIC AFFAIRS OFFICE, MS P355
LOS ALAMOS, NM 87545

DATELINE: LOS ALAMOS

power." West said. (To obtain three-fourths power of body mass, take the square root of the square root of an animal's weight and cube it.) The law, known as Kleiber's Law, had been around for decades but no one understood the reason for it, West said. "A cat is roughly 100 times larger than a mouse, so you'd expect a cat's metabolic rate to be 100 times larger than a mouse's, but it isn't," West explained. "The metabolic rate is only about 30 times larger — a number predicted by Kleiber's Law."

For their part, Brown and Enquist were trying to solve the riddle of why the metabolic rate of plants exhibits the same quarter-power scaling phenomenon observed in animals. As ecologists, they were interested in determining how population densities and other environmental laws related to the biological laws that govern individuals.

> *"A cat is roughly 100 times larger than a mouse, so you'd expect a cat's metabolic rate to be 100 times larger than a mouse's, but it isn't."*

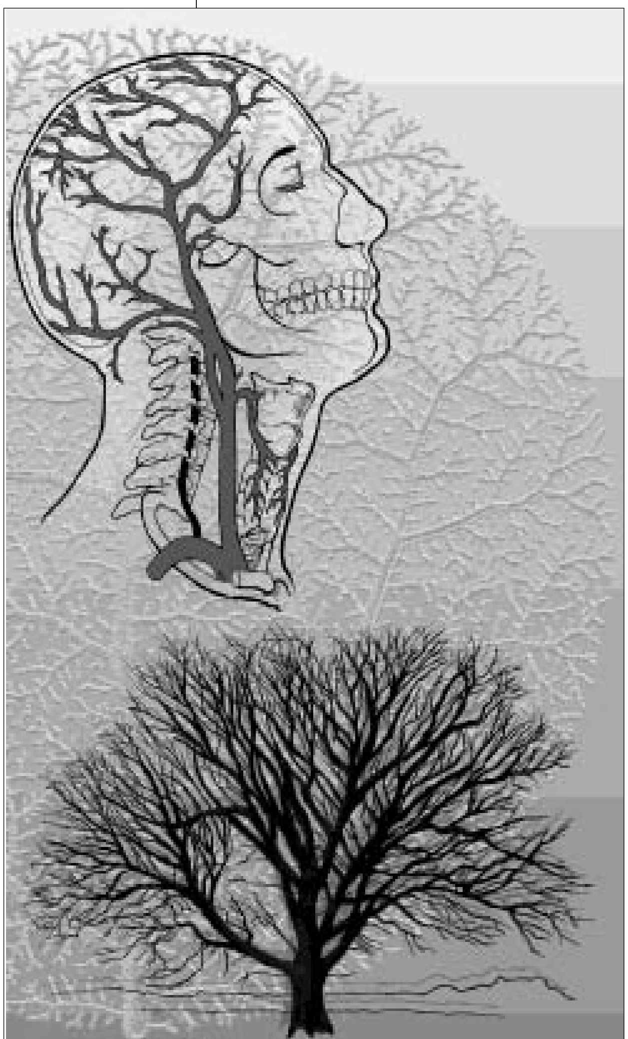
Like West, they proposed that quarter-power scaling laws arose from a common underlying mechanism: Living things are sustained by the transport of materials through a linear network that branches to supply all parts of the organism.

"Jim and I knew that the structure and dynamics of the supply network would hold the answer but we didn't have the background in physics and math to carry out the calculations," Enquist said. "Working with Geoff was like having a mind extension for physics. We could never have made the same kind of progress without him."

> *" … quarter-power scaling laws arose from a common underlying mechanism: Living things are sustained by the transport of materials through a linear network that branches to supply all parts of the organism."*

For West, the collaboration was a good way to study the bigger problem of scaling. "Jim and Brian didn't know the physical and mathematical details to build a precise model," he said, "but their intuition about living systems was tremendous. I'd crank something through the model, obtain results, only to have them shake their heads and say, 'It really couldn't work that way in a living system.' They kept me from running up a lot of blind alleys."

The researchers built their model on three assumptions: that a space-filling fractal-like branching pattern is required to supply life-sustaining fluids to all parts of the organism; that the final branch of the network — the twigs of a tree or the capillaries of a circulatory system — are the same size regardless of a species' body mass; and, that the energy used to transport resources through the network is minimized.



←

Fractal branching networks are natural structures for transporting nutrients to every cell in an organism's body.

The first assumption came from the researchers' observation that a space-filling branching network is a natural structure for transporting nutrients to every cell in an animal's body. Thus, the billion-plus cells present in the human body are fed regularly through the cardiovascular system, which transports oxygenated blood through the aorta and decreasingly smaller arteries, and through about 10 billion capillaries, each of which feeds a small number of cells.

The second assumption arose from the researchers' knowledge that all living cells — the building blocks of life — are the same size regardless of an organism's species or body weight.

Lastly, to minimize the energy required to transport resources through the system, the network had to be a "fractal branching network." Fractals are structures that exhibit self-similarity in the manner of Russian nested dolls or snowflakes. The smallest fraction of the system is a miniature replica of the entire network, the only difference between the two being one of scale.

While fractal branching networks exhibit the same type of self-similarity as nested dolls and snowflakes, their organization is tree-like. Cardiovascular systems, respiratory systems, plant vascular systems, river systems, and insect tracheal tubes are all examples of fractal branching networks. "When it comes to energy-transport systems, everything is a tree," West said.

Plant vascular systems follow the "vessel-bundle" structure of multiple parallel tubes. In this easy-to-model type of network, fluid velocity is constant throughout the network, independent of tube size. This property arises from the "area-preserving" nature of the network. Each time a tube splits into smaller tubes, the cross-sectional area of the larger tube is the sum of the smaller cross-sectional areas of the two daughter tubes.

> *"Fractals are structures that exhibit self-similarity in the manner of Russian nested dolls or snowflakes. The smallest fraction of the system must be a miniature replica of the entire network, the only difference between the two being one of scale."*

Mammalian energy-transport systems are a bit trickier to model. The branching cannot be entirely area-preserving because blood must slow down in mammalian systems to allow materials, such as oxygen, to diffuse across capillary walls.

The difficulty is solved by the heart, which pumps blood into the aorta and larger arteries in waves. The waves damp down and disperse as they leave the larger area-preserving vessels of the system and travel through the progressively smaller cardiovascular tubes. A crossover from the pulsatile waves in the aorta and larger arteries to an almost steady oscillatory flow in the smaller transport vessels ensures that energy-carrying waves are not reflected back up the tubes at branch points.

> *"Cardiovascular systems, respiratory systems, plant vascular systems, river systems, and insect tracheal tubes are all examples of fractal branching networks. 'When it comes to energy-transport systems, everything is a tree.' "*

The crossover from one kind of traveling wave to another kind is achieved through "impedance matching," an exact analog of the impedance-matching phenomenon that occurs at the junctions of electrical transmission lines. By making the total opposition to current flow in an alternating-current circuit equal to the amount of current, the most efficient transfer of power is achieved. The cardiovascular system has inherent features, such as vessel-wall thickness and elasticity, to pull off the same kind of impedance matching at its crossover branch points. The system loses a small amount of energy after the crossover, ensuring the blood moves slowly enough for oxygen to diffuse across capillary walls.

"Given the physical and geometric constraints implicit in these three principles, out pops quarter-power scaling," West said. The model accurately predicts the structural and functional properties of the mammalian cardiovascular and respiratory systems. For example, given the body mass of an adult male, the model can churn out the length and cross-sectional area of his aorta. The researchers plan to test other predictions, but their work so far suggests that quarter-power scaling is perhaps the single most pervasive theme underlying all biological diversity.

“Scaling laws mean that organisms of different sizes use energy and other resources at different rates,” Brown said. “They also operate at different spatial and temporal scales. For example, a bacterium lives fast and short with a life span measured in minutes, in a space measured in millimeters. Contrast that with a human or whale that lives for decades and moves over a space of hundreds or even thousands of kilometers.”

↑ Los Alamos physicist Geoffrey West (left) and University of New Mexico biologist Jim Brown at the Santa Fe Institute.

The quarter-power scaling laws are obeyed with remarkable precision, for body sizes over 25 orders of magnitude, ranging from single-cell organisms to blue whales. The scaling laws are also unaffected by the exact details of a system’s design as long as it has a fractal nature.

Although the model addresses fractal branching networks on the macro-biological level, the researchers predict that microscopic systems will exhibit the same fractal patterns and obey the same laws of quarter-power scaling. A paper describing their research results, titled “A General Model for the Origin of Allometric Scaling Laws in Biology,” appeared in the April 4 issue of *Science*.

In the 1950s, physicist Francis Crick and biologist James Watson collaborated on research that unmasked the double-helical structure of DNA, the twisted ladder of chemicals that serves as the blueprint for all life. Like the double-helix, quarter-power scaling is an elegantly simple design principle from which an infinite number of biological variations are possible.

Given the constraints under which life developed and evolved, it isn’t surprising that the diversity of living and fossil organisms is based on elaboration of a few successful designs, Brown said. Asked if he thought their work was as scientifically important as Watson and Crick's, Brown mused that both collaborations were a marriage of biology and physics. Pressed harder for an opinion, he demurred.

"We can't be the judges of that," West added with a laugh. "But we hope our research will stimulate more intersection between physicists and biologists."

"Scientists today are incredibly partitioned into their own disciplines," Enquist said. "Even within biology, we are partitioned into cell physiology, anatomy, ecology and so on — and each sub-partition has its own department, journal, and language."

West nodded in agreement. "We need to return to seeing things as a whole." He lamented the passing of the "natural scientists" like Sir Isaac Newton and Charles Darwin who were versed in life and physical sciences. "They were the renaissance men of science."

Human attempts to build energy-transport systems are crude and inefficient compared to nature's fractal branching networks, Brown said. "The gas turbine engine is nonfractal and incredibly inefficient, with one fuel line servicing four cylinders. That's four units versus 10 billion cells serviced by the human cardiovascular system." Most man-made systems exhibit third-power scaling. To optimize efficiency, engineers should look to nature, Brown said. Natural energy-transport systems exhibit much more branching than manmade systems, which tend to look like grids.

"It would be incredibly difficult to engineer a fractal branching system," he added, "but advanced computer circuitry comes much closer to nature's fractal geometry than the gasoline engine."

CONTACT: GEOFFREY WEST

THEORETICAL DIVISION

(505) 667-5382 • E-MAIL: gbw@lanl.gov

DATELINE: LOS ALAMOS

# COMPUTER MODEL SIMULATES GLOBAL CLIMATE EFFECTS OF MOUNT PINATUBO ERUPTION

## SULFATE AEROSOLS DEPLETE EARTH'S OZONE LAYER

A Los Alamos global climate model accurately simulated the environmental changes caused by the 1991 eruption of Mount Pinatubo in the Philippines.

➔ Mount Pinatubo erupts in 1991.

Photo courtesy of AP/World Wide Photo

When the mountain erupted for a two-month period in 1991, punctuated by a major eruption on June 15, it spewed millions of tons of sulfur compounds into the atmosphere. About a month later, the sulfate aerosols had formed a wide band in the lower stratosphere around the middle latitudes of Earth. This, in turn, began a cycle of environmental damage on top of what had already been suffered by Filipinos who felt the mountain's fury firsthand.

Sulfate aerosols play an important role in the chemical reactions that help deplete Earth's ozone layer. In aerosol form, the sulfur dioxide mixes with water vapor and forms sulfuric acid, an important catalyst in ozone depletion reactions.

When ozone depletion occurs, it has a bit of a cooling effect because ozone normally acts as a greenhouse gas by trapping heat from surface-emitted terrestrial radiation; it also absorbs direct sunlight. In addition, ozone depletion reactions involving sulfate aerosols work better at lower temperatures. For these reasons, Los Alamos researchers predicted that volcanic eruptions might play an important role in ozone depletion worldwide.

To test their hypothesis, they and their colleagues from the University of California at Los Angeles used the Los Alamos global climate model to simulate what effects the Mount Pinatubo eruption might have had on Earth's global climate. The simulation was run in mid-1993 and concluded that the amount of sulfate aerosols released by the eruption was ideal to promote sustained ozone depletion reactions. In fact, the model indicated that Earth's ozone layer would deplete by at least 12 percent during the winter of 1992-1993. Satellite data collected that winter indicated that the ozone levels had depleted by about 15 percent.

Even more significantly, the Los Alamos global climate model suggested that a wind vortex encircling the Arctic, which traps and segregates ozone and ozone-destructive chemicals during the winter months and gives rise to an uninterrupted period of ozone depletion, would remain for a longer period than normal after the eruption.

During the winter, less sunlight reaches the pole and the area becomes colder. Prevailing westward winds begin to circle the pole until a vortex surrounds a center of calm where ozone and ozone-depleting chemicals can interact undisturbed. When the region warms during spring months, the vortex breaks and the trapped air mass begins mixing with mid-latitude air masses.

Because there was a depletion of ozone levels during the winter of 1992-1993 and associated cooling effects, the researchers expected the polar vortex to last longer than usual due to the area inside the vortex remaining colder longer. There was some evidence that the polar vortex broke up later than normal.

The researchers say their ultimate goal is to develop a very accurate three-dimensional model including comprehensive chemistry that will help them understand the intricacies of the global climate. The 1991 Mount Pinatubo eruption afforded an easy way to test and validate the Los Alamos model.

Funding for the global climate model and related research comes in part from the Los Alamos Institute for Geophysics and Planetary Physics and the Laboratory Directed Research and Development program.

CONTACT: JIM KAO
ATMOSPHERIC AND CLIMATE SCIENCES
(505) 667-9226 • E-MAIL: kao@lanl.gov

DATELINE: LOS ALAMOS

# BREAKING AND ENTERING IS THEIR BUSINESS

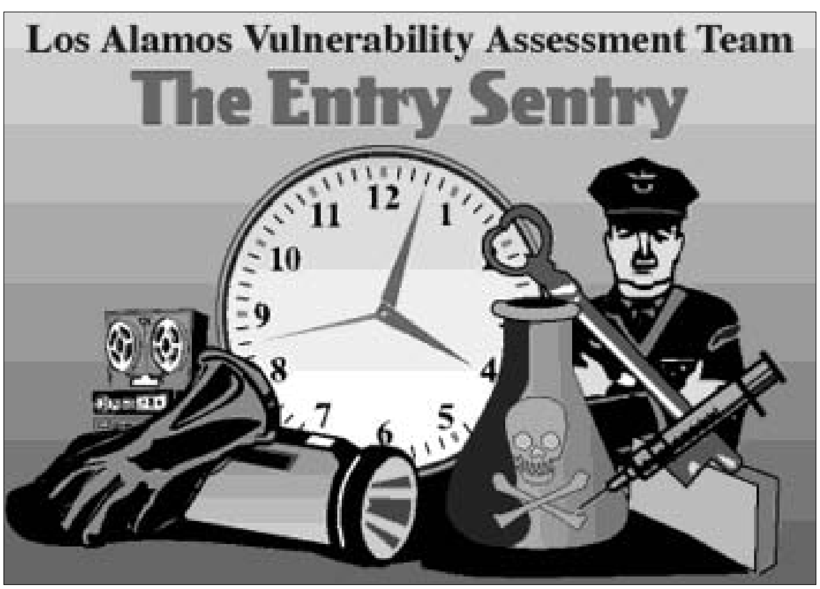
## LOS ALAMOS RESEARCHERS TEST TAMPER-RESISTANT SEALS

Tamper-resistant seals protect everything from aspirin containers, to peanut butter jars, to military cargoes. Their purpose is not to prevent entry but to leave obvious evidence of any illicit trespassing.

The purpose of the Los Alamos National Laboratory Seal Vulnerability Assessment Team is to get past tamper-resistant seals without leaving a trace. So far, the team has been able to defeat every seal it has tampered with, 98 different types in all. The average amount of time it takes to get past a seal and erase all evidence of tampering is 4 minutes.

The researchers use rapid, low-tech methods to break and enter. Most of the attacks are possible with tools from a hardware store and a standard machine shop.

Funded by a variety of government agencies and private companies, the Los Alamos team invades the supposedly protected device, building, or product to learn how to make tamper-resistant seals work better while uncovering probable scenarios of tampering.



# DATELINE: LOS ALAMOS

↑ The tamper team (left to right): Roger Johnston, Anthony Garcia, and Kevin Grace.

The seals are widely used in industry and government for a variety of applications including access and inventory control, records, shipping integrity, hazardous material accountability, theft prevention, tests for illegal drug use, and protecting consumer products. Sales of tamper-resistant seals are more than $200 million annually.

The research team defeated the seals tested in times ranging from 3 seconds to 2 hours. The majority of the attacks involved opening a seal, then resealing it and repairing any damage caused by the tampering. The team believes its work is the most comprehensive vulnerability assessment of tamper seals ever carried out.

The team's major finding is a disturbing one: All of the seals it examined could be defeated quickly and easily. Another surprising finding was that costlier seals are not necessarily better seals. In fact, the team determined that every additional dollar spent on producing the seal added less than 1 second to the defeat time.

Instead of panicking about the vulnerability of tamper-resistant seals, the researchers recommend that the public, government agencies, and industry become better educated on how tamper seals can be fooled and what to watch for. They believe most of the seals can be greatly improved by changing how the seal is manufactured, installed, or inspected. They also believe that encouraging security personnel to be aware of the most likely attack scenarios and watching for these attacks would greatly improve tamper detection.

The team welcomes inquiries from tamper-resistant seal users and manufacturers who are interested in improving their training or product.

CONTACT: ROGER JOHNSTON
ADVANCED CHEMICAL DIAGNOSTICS
AND INSTRUMENTATION
(505) 667-7414 • E-MAIL: roger_johnston@lanl.gov

DATELINE: LOS ALAMOS

## BRIEFLY ...

A LOS ALAMOS TEAM HAS BEEN RECOGNIZED FOR ITS CONTRIBUTIONS TO REDUCING AUTO EMISSIONS. The team — Antonio Redondo, Holmann Brand, James Coons, William Earl, Alan Graham, Raymond Steele, and Mark Paffett — won the award for its work in reducing emissions of nitrogen oxides from diesel and gasoline engines. The team's research centers around the development of a "lean-burn" engine that will burn gasoline more efficiently than current models. By adding more air to the fuel during combustion, the new engine design burns almost all the hydrocarbons in the fuel. The Los Alamos team helped develop a new kind of high-temperature catalytic converter than can adequately reduce emissions of nitrogen oxides to meet future pollution control regulations. Vice President Al Gore presented the award to the team March 31 in the Old Executive Office Building.



## IN THIS ISSUE:



Dateline: Los Alamos is available on the World Wide Web:
http://lib-www.lanl.gov/pubs/dateline.htm

LOS ALAMOS NATIONAL LABORATORY
WHERE SCIENCE MAKES A DIFFERENCE

DATELINE LOS ALAMOS

A MONTHLY PUBLICATION OF THE PUBLIC AFFAIRS OFFICE OF LOS ALAMOS NATIONAL LABORATORY

Nonprofit Organization
U.S. Postage Paid
Albuquerque, NM
Permit No. 532

LALP-97-1-5

Los Alamos
NATIONAL LABORATORY