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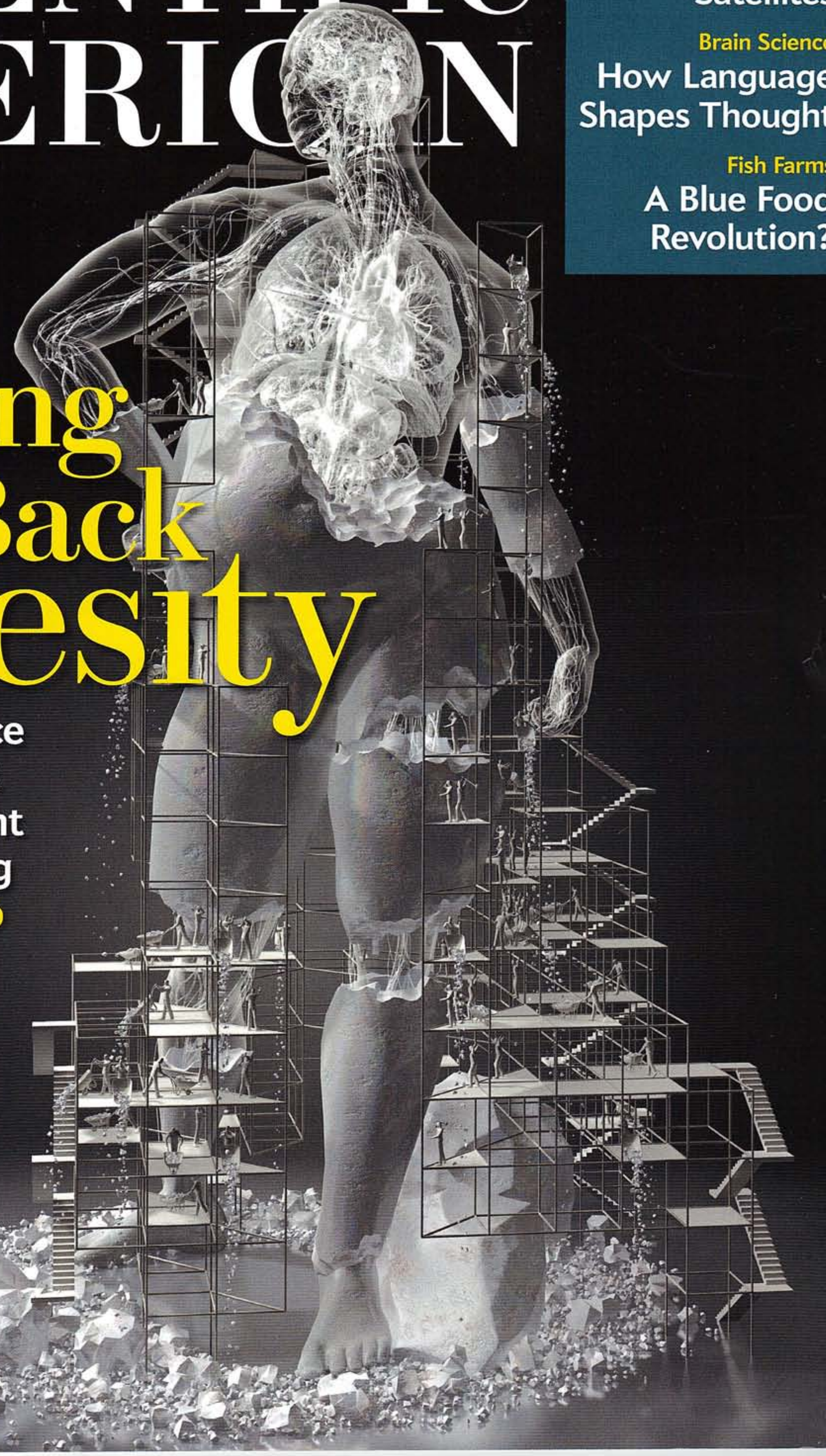

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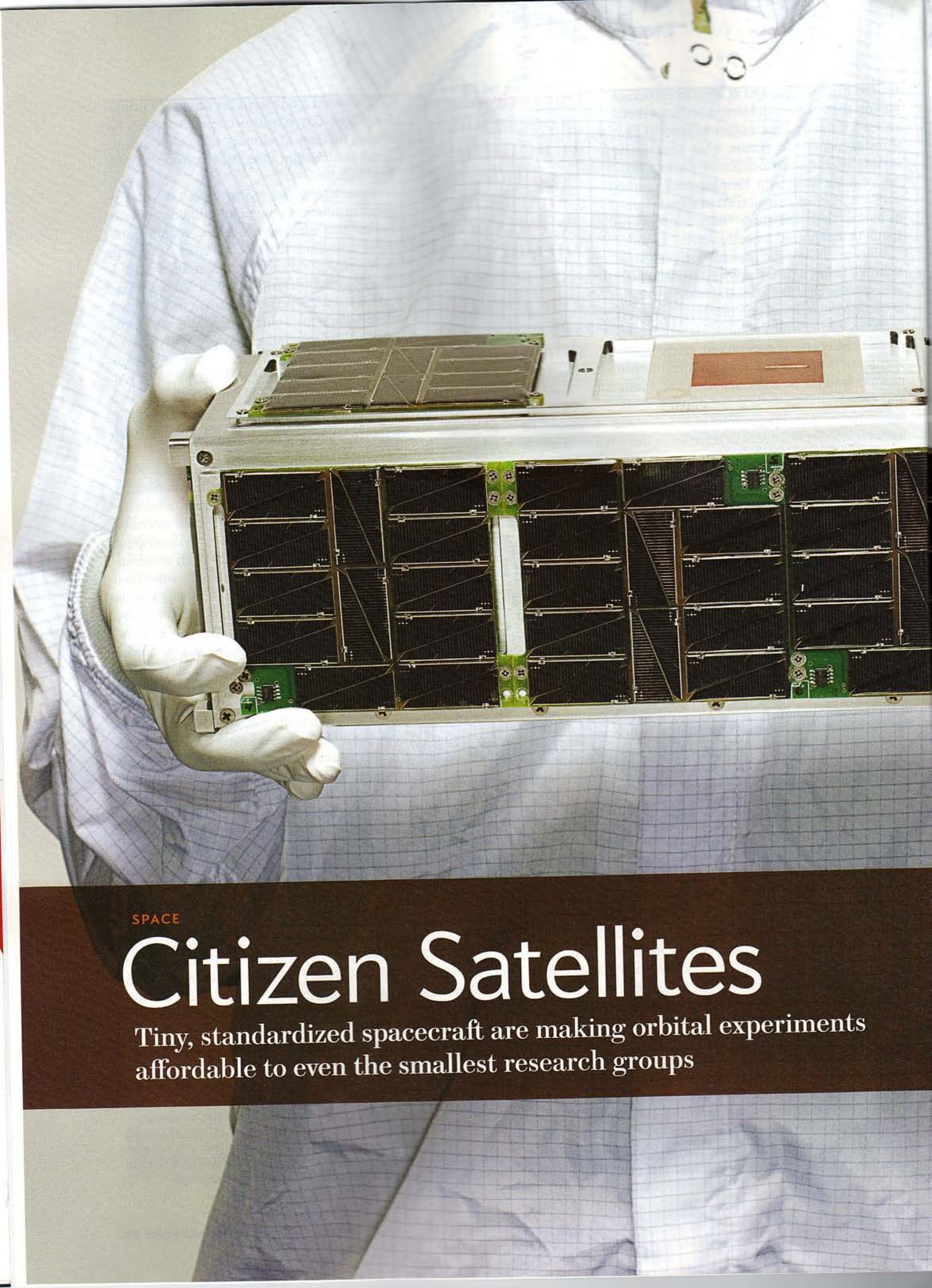
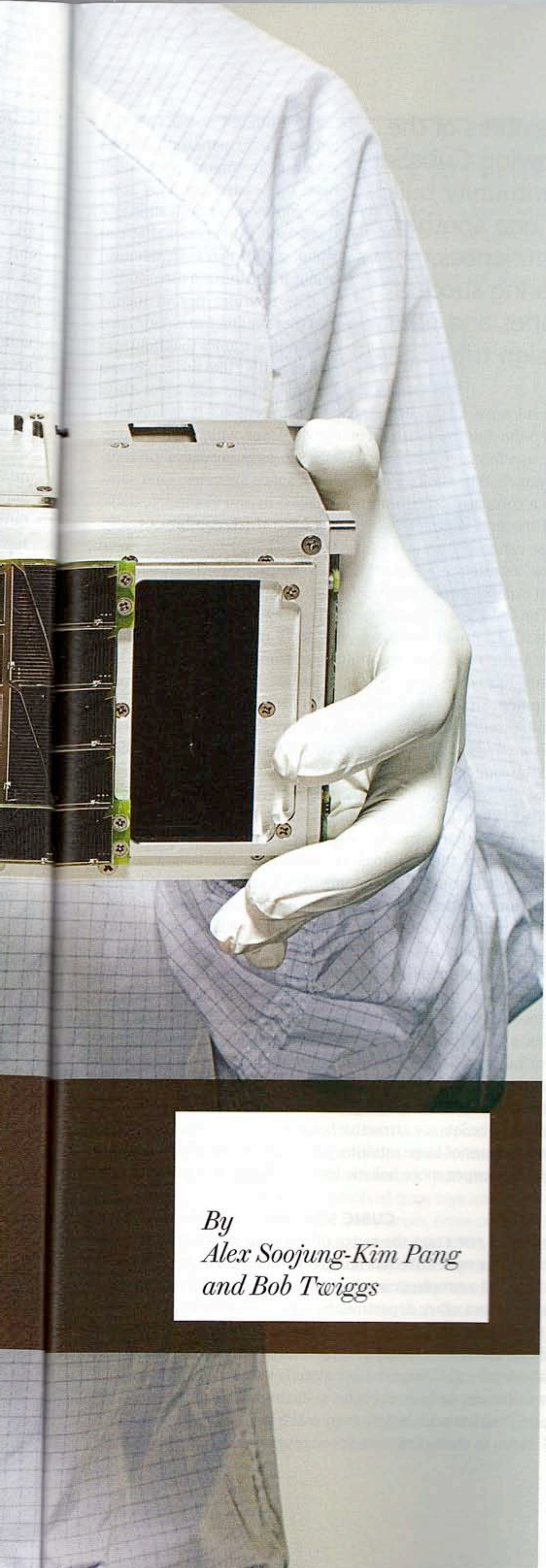


SPACE

Citizen Satellites

Tiny, standardized spacecraft are making orbital experiments affordable to even the smallest research groups



By
Alex Soojung-Kim Pang and Bob Twiggs

Alex Soojung-Kim Pang holds a Ph.D. in history of science from the University of Pennsylvania and has written on the history of astronomy, scientific fieldwork, and the social impacts of emerging technologies. He is an associate fellow at University of Oxford's Saïd Business School and is currently a visiting fellow at Microsoft Research Cambridge.

Bob Twiggs was one of the originators of the CubeSat concept while at the department of aeronautics and astronautics at Stanford University. Since 2009 he has been a professor at Morehead State University in Kentucky. Twiggs has a B.S. in electrical engineering from the University of Idaho and an M.S. in electrical engineering from Stanford.

EVER SINCE SPUTNIK KICKED OFF THE AGE OF SPACE SATELlites more than fifty years ago, big institutions have dominated the skies. Almost all the many thousands of satellites that have taken their place in Earth orbit were the result of huge projects funded by governments and corporations. For decades each generation of satellites has been more complicated and expensive than its predecessor, taken longer to design, and required an infrastructure of expensive launch facilities, global monitoring stations, mission specialists and research centers.

In recent years, however, improvements in electronics, solar power and other technologies have made it possible to shrink satellites dramatically. A new type of satellite, called CubeSat, drastically simplifies and standardizes the design of small spacecraft and brings costs down to less than $100,000 to develop, launch and operate a single satellite—a tiny fraction of the typical mission budget of NASA or the European Space Agency.

A CubeSat is about the size of a Beanie Baby box—appropriate, given that until recently, most scientists regarded CubeSats as little more than toys. The idea behind CubeSats is to give satellite developers standard specifications for size and weight and then combine many satellites—each made by a different group of scientists, graduate students, engineers—into a single rocket payload, usually piggybacking on other, more expensive missions that have a bit of room to share. The high expense of the rocket launch thus gets spread out over all the participants, keeping costs low. And the

IN BRIEF

A standardized technology for satellites is making space missions more affordable and accessible than they have ever been before.

These one-liter, one-kilogram "CubeSats" are often made of components that are shared among researchers. They can also can piggyback on other missions' rockets.

The satellites can take as little as one year to develop and can be linked into networks of space sensors. Most also fall to the surface in a relatively short time, which means they do not add to orbiting space junk.

Universities, companies, countries and even hobbyists can afford to do serious science missions in fields ranging from atmospheric physics to microgravity experiments.

Researchers at the University of California, Berkeley, used the standard CubeSat shape and size for their Ions, Neutrals, Electrons, Magnetic Fields project (*left*).

Photograph by Spencer Lowell

CubeSat design standards allow participants to share design features and know-how and buy components off the shelf.

Since the CubeSat concept was introduced, scientists from the U.S., Asia, Europe and Latin America have successfully launched at least two dozen CubeSats, which have performed everything from biomedical research in microgravity to studies of the upper atmosphere. CubeSats' low cost, rapid development times and global user community, combined with their value as teaching tools, have made them increasingly popular. University teams—often consisting largely of college and grad students—have sprouted around the world. CubeSats are also enabling small countries, start-up companies and even high school teams to develop their own space programs. Soon launch costs may come down to about $10,000—low enough for space amateurs to follow suit. We think that CubeSats could do for space what the Apple II did for computing 30 years ago: spark an economic and technological revolution by placing a well-known but formerly inaccessible technology in the hands of just about everyone.

LAUNCHING AN IDEA

SMALL SATELLITES, weighing a few kilograms, have been around since the beginning of the Space Age; Sputnik 1 itself weighed just over 80 kilograms. But as rockets became more powerful, satellites grew larger and more complex, to the point where a typical communications or research satellite weighs several tons.

Meanwhile "microsatellites"—spacecraft weighing between 10 and 100 kilograms—were pushed to the margins of space science but never disappeared completely. For example, atmospheric scientists sent them up to explore the thermosphere, the layer of the atmosphere that extends from about 80 kilometers to about 600 kilometers above Earth's surface, and scores of OSCAR (for Orbiting Satellite Carrying Amateur Radio) communications satellites have been helping ham radio enthusiasts connect since the early 1960s. But the potential of small satellites really began to grow in the 1980s, thanks to electronic miniaturization and the development of precision manufacturing techniques and microelectromechanical systems, such as the tiny accelerometers now common in devices from iPhones to air bags.

By the late 1990s it seemed possible to create useful satellites that weighed only a kilogram—a size that would radically reduce development and launch expenses and encourage developers to explore novel ways of designing missions. NASA also actively encouraged engineers to come up with cheaper approaches to space science.

It was then that one of us (Twiggs, then at Stanford University's Space and Systems Development Lab), together with Jordi Puig-Suari, a professor at California Polytechnic State University, San Luis Obispo, realized that to get the small-satellite concept to fly, some standardization would be crucial, as would following the example of the open-source movement, which cheaply creates world-class software. So in 2000 the two engineers published the CubeSat specifications. The 10-page document established some simple prescriptions: each unit must be a cube of 10 centimeters on its side (plus or minus a tenth of a millimeter) and thus have a volume of one liter. It also must not weigh more than one kilogram. CubeSats can also be rectangular, taking up the space of two or three boxes with a single physical unit; those are called 2U or 3U CubeSats.

A CubeSat consists of a metal frame that contains and protects the electronics, instruments, communications and energy systems within it. CubeSats also often have solar panels on several sides and an antenna protruding from one end; some may soon have rudimentary navigation systems, with tiny nozzles that can stabilize the craft's attitude and orient it in a desired direction.

Members of the growing CubeSat community build on one another's experiences, sharing success stories and new design tricks.

The modular design means that the satellites can be launched in standard frames that hold several at a time, like the candy in a Pez dispenser, and eject their payload once the rocket reaches orbit. In 2003 Puig-Suari released the design of such an orbital deployer, which made it possible to safely carry and launch CubeSats as "stowaways" on rockets launched by the U.S. and Russian space agencies. That same year a company called Pumpkin, based in San Francisco, delivered the first commercial CubeSat kit—which combines ready-to-use components such as an electronics motherboard, a metal frame, a battery and solar panels to enable scientists with little or no experience in space missions to hit the ground running.

The CubeSats' innards are as diverse as the teams that build them. Open one up, and you may see a mix of aerospace hardware and off-the-shelf technology; customized scientific instruments; hardware recycled from earlier space missions; radio equipment from local electronics shops; or computer hardware cannibalized from PCs or purchased on eBay.

From the beginning, members of the CubeSat community have built on one another's experience, success stories and design tricks; newcomers quickly learn that you share everything but the payload. When developers find something that works—one model of ham radio that works in space longer than another, for example—they share their findings with other CubeSat designers.

Soon we learned that students liked CubeSats, too, and could learn a lot from them. Students in traditional aerospace engineering programs work on theoretical projects or design small parts of large systems that go into space years after they graduate. A CubeSat, in contrast, is an object students can literally get their hands around. It can be built by a team working together in a single room. Students can create working satellites in a year or two, which makes them ideal thesis projects. They get hands-on responsibility on CubeSat projects: even undergrads can be project managers and mission specialists, and the possibility of seeing their work go into space is a great incentive to work hard. For educators, CubeSats are attractive because they present all the engineering issues of large satellites and thus offer students a way to acquire a deeper, more holistic feel for satellite design.

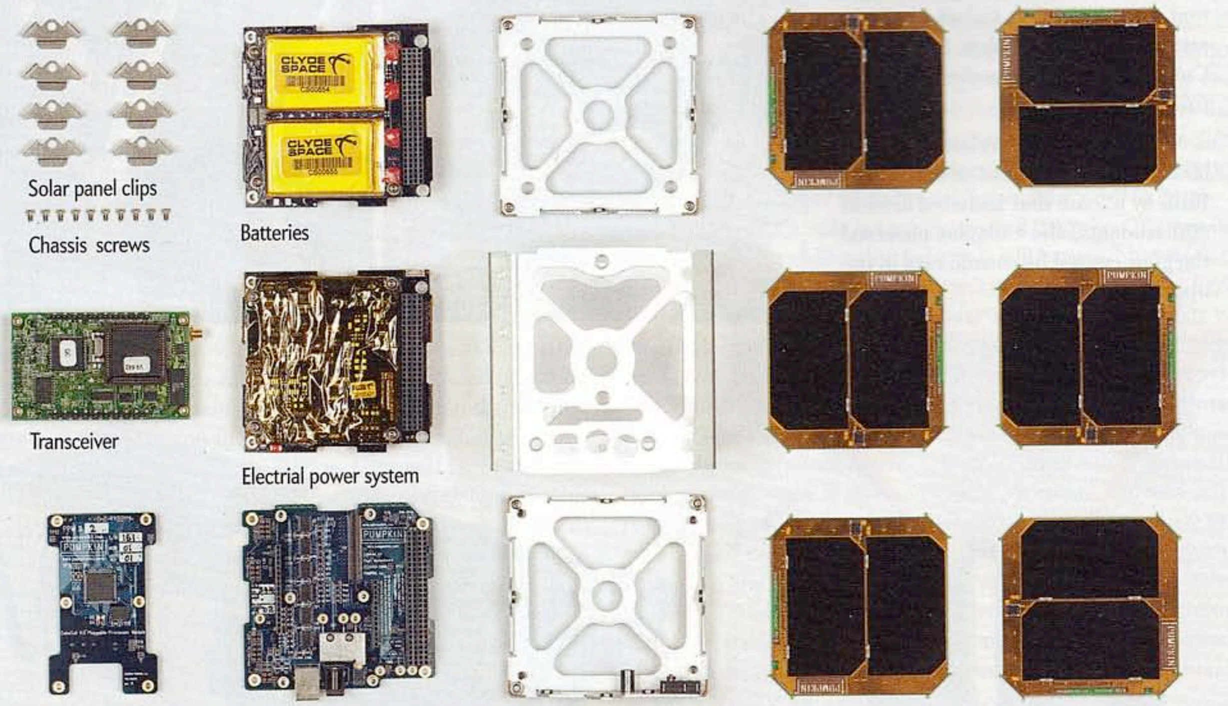
CUBIC SCIENCE

IN THE PAST FEW YEARS the range of scientists and institutions experimenting with CubeSats has greatly diversified. Aerospace engineers and astrophysicists have been joined by professors and students from other departments, and entrepreneurs have started companies offering launch services and support. Countries without much of a space program have been able to start one. Switzerland and Colombia have already launched their countries' first CubeSats, and several others—including Estonia—are working on their own. CubeSats even make it possible for individual U.S. states to start their own space programs. Most notably, Ken-

THE GEAR

The Guts of a CubeSat

Ready-to-use assembly kits—such as one available from Pumpkin in San Francisco for $7,500—and other off-the-shelf parts give teams of scientists and engineers a chance to focus on the instruments for their experiments, rather than having to design entire spacecraft from scratch. The image below shows some parts from Pumpkin's kit (flight computer, solar panels and structural components) and some additional parts (Scotland's Clyde Space power system and batteries and a radio transceiver from Canada's Microhard Systems).



tucky has formed a consortium of academic and nonprofit institutions to build a CubeSat industry.

The state of the art has also moved from educationally oriented demonstration missions—"BeepSats," as early projects have been dubbed, because they often did little more than transmit radio signals to confirm that they were alive and prove that small satellites could communicate with stations on Earth—to more serious science. As NASA technologist Jason Crusan puts it, the CubeSat community can now point to a "critical mass of successful and significant missions that have shown results" and answer the objections of critics. CubeSats have evolved from toys into tools.

Those tools are being used in many areas, some controversial or highly experimental. QuakeSat, launched in 2003, was part of an effort to better predict earthquakes by detecting extremely low frequency (ELF) magnetic field changes. QuakeSat operated for a number of months and successfully sent back data to its ground station at Stanford, although most seismologists remain skeptical of a causal relation between ELFs and earthquakes or of the value of space-based ELF detection. Another example is LightSail-1, a 3U CubeSat designed by the Planetary Society to test the world's first solar-wind sail, a technology that could someday become a viable mode of propulsion around the solar system.

NASA, intelligence agencies and the military are also starting to experiment with CubeSats. This change of heart is remarkable given that a few years ago, mainstream space scientists believed that CubeSats would never be powerful or sophisticated enough for real science or surveillance, could not be maneuvered or controlled precisely, and would add space junk in valuable low Earth orbits. Even as microelectronics, sensors, batteries and other systems components improved, organizations accustomed to spending hundreds of millions of dollars and thousands of man-years to create satellites the size of automobiles still could not imagine that a quickly made satellite the size of a shoebox could be worth any attention.

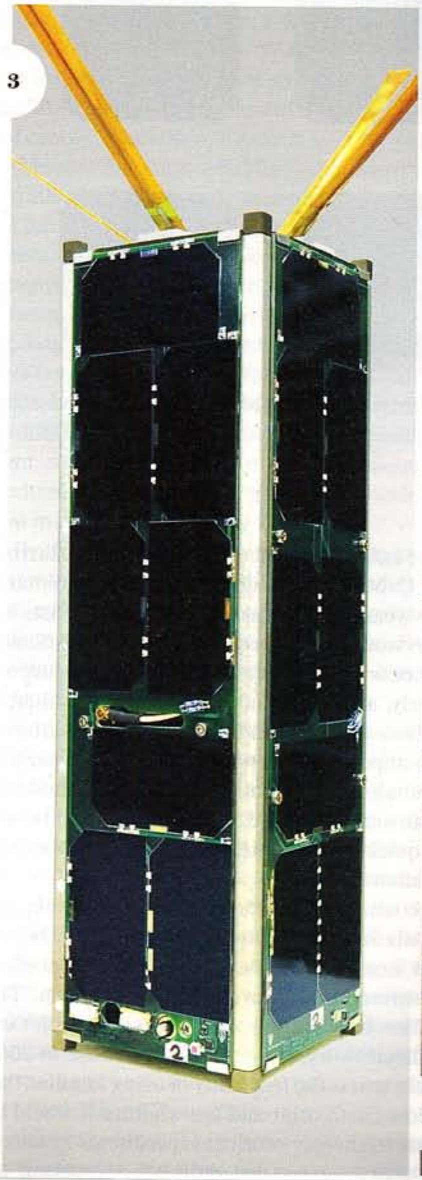
The National Reconnaissance Office's Colony 1 program, for example, is using CubeSats to test-fly new technologies before they are installed on larger craft. Other scientists have CubeSats performing more conventional pharmaceutical research. The Small Spacecraft Office, based at the NASA Ames Research Center in California's Silicon Valley, launched two CubeSats in 2006 and 2007, respectively, to test the feasibility of using familiar "lab on a chip" tools in low Earth orbit and see whether it would be possible for biologists to cheaply conduct experiments in microgravity. Three years later the group tested the effectiveness of an-

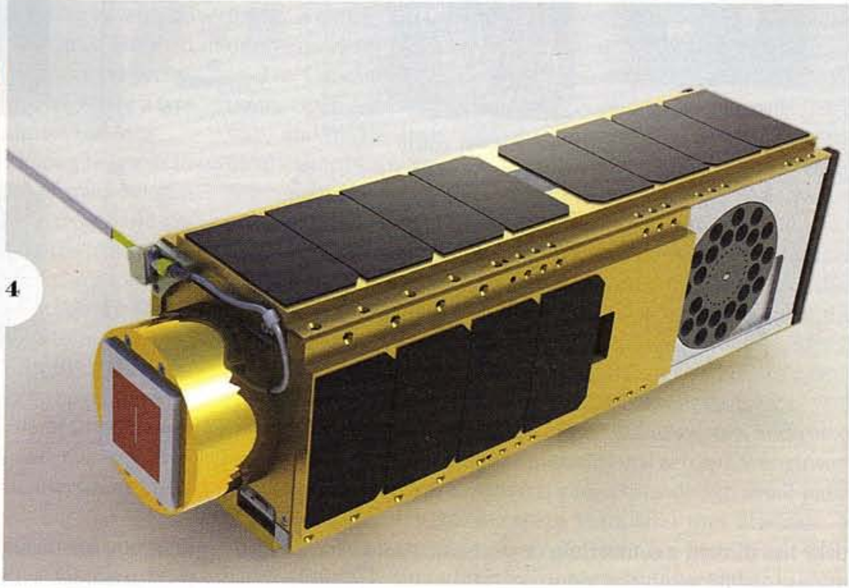
Photograph by Spencer Lowell

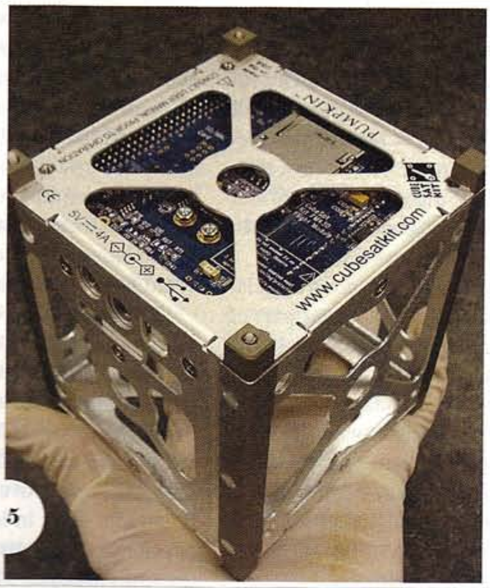
Cottage Industry of Space Science

1. Good attitude. Faculty and students at Cal Poly test a magnetic system for adjusting a CubeSat's flight attitude, in preparation for CP6, a CubeSat mission launched successfully in 2009.

2. New country. Switzerland launched its first satellite, SwissCube, in 2009. Built by a team that included around 200 students, the CubeSat observed the glow caused by cosmic rays in the upper atmosphere.







3. Space weather. The Radio Aurora Explorer, launched last November, will study how solar wind affects Earth's ionosphere. The University of Michigan and SRI International built the satellite.

4. Life. NASA's Organism/Organic Exposure to Orbital Stresses CubeSat, launched last November, will demonstrate the ability to do low-cost biology experiments.

5. Ham radio. Students at the University of Liège in Belgium are building the Orbital Utility for Telecommunication Innovation for digital radio communications.

tibacterial drugs in microgravity—the first step in designing a pharmacopeia for lengthy manned missions. And in July 2010 Houston-based company NanoRacks installed a CubeSat holder on the International Space Station and now leases space to pharmaceutical companies and other science-based industries interested in conducting research in space—as well as to educational institutions, including one high school.

Some CubeSats are devoted to weather and climate. CloudSat, designed by scientists at Colorado State University, will study vertical cloud structure and formation over a period of days, something meteorologists flying in aircraft have not been able to do. A mission supported by the National Science Foundation called Firefly will deploy a gamma-ray detector and photometer to measure terrestrial gamma-ray flashes, which shoot from Earth's atmosphere up into space, usually during lightning storms.

Both CloudSat and Firefly will observe phenomena in the troposphere, the 16-kilometer-deep atmospheric layer where humans live. Another class of CubeSats will study the thermosphere. The thermosphere is buffeted by solar wind, coronal discharges and sunspots, and its upper boundary rises and falls depending on solar activity. These changes can interfere with the performance of low-orbit satellites: the American space station Skylab crashed in 1979, when an unexpected rise in the thermosphere increased drag on the station and pulled it to Earth. Given that the International Space Station, GPS, and radio and television satellites orbit in the thermosphere, understanding this layer is as important for global communications and science as understanding the oceans is for global trade. Larger satellites at higher orbits cannot observe the thermosphere directly; instead they see it wedged between the exosphere (the thin layer between Earth and space) and the stratosphere (the layer directly below the thermosphere), while instruments on sounding rockets take direct measurements, but only in the small column of the rockets' trajectory and for a few minutes.

SEE HOW CUBESATS ARE MADE
ScientificAmerican.com/feb2011/cubesats

The first thermosphere CubeSat to reach space was Switzerland's SwissCube, launched in late 2009. SwissCube measures and maps airglow, the very faint light emitted by chemical and physical reactions in the upper atmosphere, to help scientists better understand its causes and more effectively filter it out when studying other atmospheric or terrestrial phenomena.

A NEW ECONOMY OF SPACE

PERHAPS THE MOST DISRUPTIVE innovation brought about by CubeSats has been their introduction of a new business model into the economics of space. CubeSats from different groups are usually bundled together and launched as secondary payloads. This means CubeSats launch when it is convenient for the owners of the primary payload, but flying coach saves money and distributes launch costs among many participants. Further, as Kris W. Kimel, president and founder of Kentucky Science and Technology Corporation, explains, the low cost of CubeSats "lets you fail, and it lets you innovate. That's a key to entrepreneurship." Low costs create a higher tolerance for failure throughout the design and deployment process: for CubeSats, blowing up on the launchpad or refusing to deploy once in space hurts less. (And stuff does happen: 14 CubeSats were lost in a 2006 rocket failure, and another nine made no or limited contact with ground stations.) "If you lose one, you don't like it," Kimel says. "But it's not like you've lost $5 million." Conventional satellites, in contrast, are "too big to fail," says Andrew Kalman, Pumpkin's president and chief technology architect.

Some missions take this attitude one step further: they deliberately put their CubeSats in self-destructing orbits to generate interesting data. "CubeSats can go places where they won't live very long," Puig-Suari notes. "I can make a disposable satellite that I can usefully put in hazardous locations. Not only can you tolerate failure, you can design for it and take advantage of it."

Two examples of this approach are missions that Twiggs helped to design. The first is a collaboration of European, Asian and American teams called QB50. The consortium will launch 50 double-cube CubeSats in the upper edge of the thermosphere. Over several months, as atmospheric friction slows the satellites, their orbits will decay, and they will gather information about the chemical composition, density and temperature of the thermosphere at progressively lower altitudes, until they finally fall to Earth.

The second example is a mission called the Polar Orbiting Passive Atmospheric Calibration Sphere. It will launch three 3U CubeSats to measure the heating of Earth's atmosphere by solar flares. As the satellites fly through the polar atmosphere, scientists will watch how their orbits decay and expect to learn how to better predict the relation between the thermosphere and solar activity.

CubeSats' small size and their relatively weak communications systems still impose harsh limits on an individual spacecraft's ability to gather much interesting data. This is one reason most missions have been double or triple cubes, and why scientists are now experimenting with deploying CubeSat networks in which the satellites are able to coordinate and work together, much in the same way birds flock and migrate. Developers are working on intersatellite communications, systems to permit formation flying, and even kilometers-long tethers to keep satellites joined together. Finally, the Defense Advanced Research Projects Agency is sponsoring a $75-million research project on CubeSat networks to understand under what circumstances CubeSats can replace traditional satellites. Stable constellations of CubeSats might even provide an alternative to large instruments: Gil Moore, an emeritus professor at Utah State University, envisions being able to "put up large, sparse arrays that will do what the Hubble and Webb space telescopes do."

To further extend CubeSats' capabilities, Paulo Lozano of the Massachusetts Institute of Technology has developed a tiny electronic propulsion system that would enable CubeSats to be steered. Others are working on printing CubeSat components, which would reduce costs.

Ultimately, Kalman says, scientists will be able to treat CubeSats like personal computers: they will be "a foundation on which people can build their own apps." The idea that CubeSats could be the PCs of space science—cheap, flexible, commoditized and standardized—suggests a final and potentially even more revolutionary role: enabling an amateur presence in space. This may come sooner rather than later: space start-up Interorbital Systems in Mojave, Calif., plans to offer CubeSat kits and low-Earth-orbit launch for less than $10,000. "Amateurs will have a chance to participate," Puig-Suari says. "People are going to start building their own mini Hubbles." ■

MORE TO EXPLORE

CubeSat Design Specification Revision 12. California Polytechnic State University, 2009.
The official Web site of the CubeSat project: www.cubesat.org