impair their function. The engineered virus was still able to invade bacteria and replicate, according to Endy. “We’ve demonstrated it’s possible to redesign a genome” beyond adding individual genes, he says. Now, he and his colleagues are adding more bases to the T7 genome, testing the limits of this expansion technique.

Making genomes bigger or smaller is just a tiny step in realizing the true potential of synthetic biology. The field needs to move forward on many fronts, says Venter. Synthesizing new chromosomes from scratch, for example, remains a challenge. In one effort in that direction, Smith and his colleagues have for the past few years been knocking out individual genes in Mycoplasma genitalium, which has the smallest known genome of a free-living organism (Science, 14 February 2003, p. 1006). So far, they’ve identified about 100 genes, out of nearly 500, that M. genitalium can live without.

Their eventual goal is to identify the microbe’s essential sequences and then see if they can synthesize and assemble just those sequences and use them to create a living organism by inserting the humanmade chromosome into a cell. Among the many details to be worked out, says Smith, is how to piece together relatively huge sections of DNA. Ideas include using live cells to put together chunks of DNA into a whole mycoplasma chromosome or putting an efficient DNA repair system—such as seen in bacteria resistant to radiation damage—into a test tube to accomplish this task. Then his team must determine how to stick this DNA into a cell and remove the native DNA, without affecting the cell’s ability to function.

Ethical and environmental concerns must also be dealt with before synthetic biology fully matures as a field. MIT, the Venter Institute, and the Center for Strategic and International Studies in Washington, D.C., have teamed up to examine issues such as how to keep any new life forms created under control. This effort is funded by a $570,000, 15-month grant from the Alfred P. Sloan Foundation. Some researchers are already exploring strategies to incorporate safeguards. For example, Church and Endy are developing ways to keep synthetic genetic codes from escaping and possibly wreaking havoc. One solution: Alter synthetic genetic codes such that they are incompatible with natural ones because there is a mismatch in the gene’s coding for amino acids.

A final issue confronting synthetic biology is cost. The bigger the DNA piece synthesized, the less accurate the sequence and the more expensive it is to get it right. But new technologies are rapidly coming on line, note researchers. “The cost of accurate DNA synthesis and sequencing is plummeting, and as it does, we will see a quantum shift in what people dream of and do,” says Church.

—ELIZABETH PENNISI

Forging a Cosmic Connection Between Students and Science

By deploying cosmic-ray detectors at high schools, physicists hope to inspire students and score real scientific discoveries to boot

Twelfth-grader Treasure Sheppard has aspired to become an aerospace engineer since she was 7 years old. But nothing fired the bright and bubbly 17-year-old’s passion for science and technology quite like a weekend visit to the California Institute of Technology (Caltech) in Pasadena, where she and a classmate assembled a detector to snare cosmic rays—subatomic particles zooming in from space. “I was expecting a few lectures” from Caltech physicists, says Sheppard, who attends nearby South Pasadena High School. “But when we got there, they handed us a piece of paper and said, ‘These are the instructions.’ They had confidence that we could accomplish the task.”

That detector is now part of the California High School Cosmic Ray Observatory (CHICOS), an array of detectors stretching across the roofs of 70 high schools and middle schools in metropolitan Los Angeles. Unlike typical high-school science projects, CHICOS aims to do cutting-edge research by probing the nature of cosmic rays. That prospect thrills Sheppard, who last year tended the two detectors on her school’s roof. “CHICOS gave me an opportunity to participate in research,” she says, “which some college students can only dream of.”

CHICOS is one of several arrays that have sprouted up across North America and Europe. Using salvaged parts, a little new-fangled electronic gadgetry, and student labor, particle physicists are outfitting schools from rural Nebraska to downtown Amsterdam with simple, inexpensive cosmic ray detectors. At least six sizable arrays are up and running, and as many more are in the planning. Physicists aim to stimulate teachers and students by bringing real science into the classroom. At the same time, they hope to grab scientific glory on the cheap by discovering phenomena that more-expensive research arrays might miss.

Cosmic rays enable educators to bring science to the students instead of busing the students to visit some distant lab, says Gregory Snow, a physicist at the University of Nebraska, Lincoln, and leader of the Cosmic Ray Observatory Project (CROP), an array with detectors at 26 schools across the state. “Cosmic rays are going through every high school in the world all the time,” he says. “That allows you to get people involved in research right where they live and go to school.” The National Science Foundation has funded several of the arrays, and the primary goal of the projects is education, says Randal Ruchti, a program officer in experimental particle physics at the foundation. Still, he says, it’s possible that “a student could participate in a revolutionary discovery.”

To fulfill both their educational and scientific missions, however, the projects must balance the students’ need to tinker with the detectors against researchers’ need to keep machinery running full-time. And there’s no science that can tell physicists how to strike the proper balance.

Finding a niche

Every second, hundreds of cosmic rays pepper every square meter of Earth. If a ray has enough energy when it crashes into the atmosphere, it produces a cascade of particles known as an “extensive air shower.” For decades, physicists have studied air showers with detectors arrayed on the ground, using the
size and the timing of the signals from the individual detectors to estimate the energy and direction of the cosmic ray.

Since the 1990s, physicists have known that a very few cosmic rays crash into the atmosphere packing as much energy as a large hailstone. No one knows how an individual subatomic particle obtains such tremendous energy or precisely how often one strikes. Professional cosmic ray arrays—most notably the Pierre Auger Observatory, an array of 1600 detectors stretching over 3000 square kilometers currently under construction in Argentina—focus on those questions.

But some physicists hope to build arrays on the cheap by placing detectors on the roofs and grounds of schools—and more than one claims to have had the idea first. The detectors typically consist of sheets of plastic “scintillator,” which emit light when penetrated by charged particles. Often, as is the case with CROP and CHICOS, the scintillators are left over from decommissioned professional arrays. For a few thousand dollars, researchers outfit a school with its own miniarray of a few detectors, a Global Positioning System station to tell precisely where each detector is and when it registers a hit, and a computer to collect data and ship it to the researchers via the Internet.

The arrays differ in essential details. For example, the schools in CHICOS are as little as a kilometer apart, so several may register hits from a single large shower. Schools in CROP are separated by hundreds of kilometers, so even a big shower will likely strike only one. Some arrays are more polished and professional than others. For example, physicists build the detectors for the Alberta Large Area Time Coincidence Array (ALTA), which is run by the University of Alberta in Edmonton and has detectors at 15 schools. In contrast, high-school students cobbled together the detectors for the Washington Large Area Time Coincidence Array (WALTA), which is run by the University of Washington, Seattle, and has detectors at 11 schools. “Ours is more of a roll-your-own approach,” says Jeffrey Wilkes, a particle physicist at the university.

High-school arrays cannot compete toe-to-toe with Auger, says Mark Pearce, a particle physicist at the Royal Institute of Technology in Stockholm, Sweden, and leader of the Stockholm Educational Air Shower Array, an array of detectors at the institute and four secondary schools around the city. But “there are theories that the professional arrays are not designed to test, and certain interesting, well-defined questions that these school arrays might be able to answer,” he says. For example, with schools spread over even larger areas, the arrays might test whether cosmic rays arrive in widespread bursts instead of completely at random. That could happen if an iron nucleus from space collided with a photon from the sun and splintered into pieces.

Some researchers hope to carve out a niche by literally looking where Auger cannot.

Auger observes only the southern sky, which may differ from the northern sky when viewed in cosmic rays, notes Robert McKeown, a particle physicist at Caltech and leader of CHICOS. “We are the largest array in the Northern Hemisphere,” he says, “and if an unusual event occurs in the Northern Hemisphere, we may be able to see it.”

Others hope to use high-school arrays to develop new detection techniques. Physicist Helio Takai and colleagues at Brookhaven National Laboratory in Upton, New York, plan to use a high-school array on Long Island to test an antenna that detects radio waves reflected by the charged particles in an air shower. They’ve dubbed their project Mixed Apparatus for Radio Investigation of Atmospheric Cosmic Rays of High Ionization, or MARIACHI. By comparing readings from the array with those of the antenna, Takai and colleagues hope to show that the low-cost radio technique is effective.

Unanswered questions
Regardless of their specific scientific goals, all the arrays hope to spark students’ interest in science. And some students say that the projects have succeeded handsomely. Mark Jeroncic participated in ALTA while he was a student at Edmonton’s Holy Trinity High School. Using data collected with his school’s detectors, he found a correlation between the rate of cosmic rays and ozone levels in the city. Now in his second year at the University of Alberta, Jeroncic says his experience with ALTA led him to major in physics.

Most physicists recognize that reaping a rich data harvest may conflict with giving students a chance to take the detectors apart and fiddle with them to see how they work. And they disagree about which aspect projects should emphasize. “We think that the real thrill for the students is to be part of a research project, so we’ve always strived to make this a professional array,” says James Pinfold, a physicist at the University of Alberta and leader of ALTA. To that end, ALTA researchers build and install the hardware. “We give the students the data to play with rather than the detector,” Pinfold says. ALTA physicists give students smaller scintillator detectors to use in classroom experiments.

But students may feel little connection to the main array if they never get to touch it, says Charles Timmermans, a particle physicist at Raboud University in Nijmegen, Netherlands. Timmermans heads the High-School Project on Astrophysics Research With Cosmics (HiSPARC), an array with 35 miniarrays at schools in Nijmegen, Amsterdam, and other cities. “Small detectors are nice, but you have to give students the feeling that the array on the roof is theirs,” he says. “If you don’t give them a chance to work and play with it, I think that after the first generation of students, that feeling will fade pretty fast.” Timmermans favors designating a week each year to let students rebuild the detectors.

Ultimately, it may be hard to predict what will inspire any individual student. Loran de Vries, who attended the Amsterdams Lyceum and participated in HiSPARC, says he was most impressed by the inability of physicists to answer basic questions about the origins of high-energy cosmic rays. “I saw with my own eyes that in this subject, most of these things are not known, and I found that fascinating,” says De Vries, currently a second-year student at the University of Amsterdam. Thanks in part to his experience with HiSPARC, De Vries wants to become a high-school physics teacher. Perhaps when the time comes, he’ll be able to answer those questions for his own students.

—Adrian Cho