electrical pulse down the electrode while the bird was singing disrupted the song. Pulses to the RA just caused the birds to make a small mistake—perhaps dropping a note. But a pulse to the HVc stopped their singing altogether for a moment, and the birds would start that part of the song over again.

As a result, Vu concluded that the HVc contributed at a higher level, perhaps by defining syllables or sequences of syllables, while the RA conveyed instructions about the notes needed to create syllables. But to actually prove that, neuroscientists needed to see the actual firing patterns of the neurons controlling bird song. And that is what Margoliash and Yu have provided in their current work.

For their experiments, Yu and Margoliash first outfitted 13 male birds with brain electrodes, projecting into either the HVc or the RA. These electrodes were in turn connected to a computer that recorded and analyzed the electrical impulses from individual neurons in the two brain centers as the birds sang. Because Margoliash also kept track of what sounds the birds made as various cells fired, the researchers could compare the activity of these different cells at the same point in the bird's song, which it repeats over and over again.

These comparisons showed, Margoliash says, that each HVc cell measured had a signature firing pattern that differed from cell to cell but corresponded to a specific syllable. These patterns weren't apparent at first, however, because of what Margoliash calls their "sloppiness." The firing patterns were variable both in the number of bursts in a series and the time between each series. But by lining these patterns up with the corresponding sound recordings, Yu and Margoliash found that the patterns did have subtle similarities, with some characteristic pauses and a recognizable, although not identical, series of bursts for each syllable. Eventually the researchers were able to predict the syllable to be sung just by looking at these patterns.

In the RA, in contrast, the firing patterns were much easier to discern, because the timing of firing varied very little from one round of singing to the next. And in this region of the brain, the patterns seem to correspond generally to individual notes rather than syllables. "As you get closer to the muscles, [the brain] is breaking [the message] down into smaller and smaller units," explains Allison Doupe, a neurobiologist at the University of California, San Francisco. "The precision of the timing [in nerve cells] gets more and more exact." Thus by the time the signal to sing reaches the muscles, that signal has been broken into very specific commands that synchronize each muscle contraction.

Yu and Margoliash have also shown, as Doupe puts it, that there is information not only in neuroscientists' traditional focus, "the neuron turning on and off, but also in the timing of when it goes on and off." In a given RA nerve cell, for example, the researchers found that two bursts of activity with almost no pause in between seem to lead to a different note than, say, three bursts with a slight pause after the first, or two bursts with a long pause between them.

And because Yu and Margoliash could look at the individual activity of several nerve cells at the same point in the generation of the song, they could also see how the combined temporal patterns of groups of cells can have specific meaning to the cells receiving this input. Somehow, the input from several HVc cells, with each firing according to its syllable-specific pattern, sums together to communicate to the RA cells what notes need to be generated for that particular syllable. "It's clear that the brain is a temporal pattern processor," says Margoliash.

Just accomplishing these kinds of measurements in birds was "quite a significant feat," says Doupe. Male finches sing only when they are at ease, and any recording system has to cope with their tendency to puff up their chests and hop about when they sing. Indeed, Margoliash says, he and Yu struggled for a long time to design a workable technique. "We had years where we got virtually no data," Margoliash recalls, until they finally designed a light and robust recording device.

The work should aid more than just future zebra finch studies, because it has possible implications for how the human brain controls speech. Indeed, neuroscientist John Middlebrooks of the University of Michigan, Ann Arbor, suggests that its implications may be even wider. He points, for example, to an intriguing tie between Yu and Margoliash's findings and his own studies of how the ear responds to sounds. Middlebrooks has found that when nerve endings in the ear are stimulated they send a very precise signal to the brain, much like the precise signal the RA sends to the throat muscles in a singing finch. Then as the sound's message travels to ever higher brain centers, it becomes ever more abstract, he notes—Yu and Margoliash's hierarchy in a new setting.

Moreover, Middlebrooks suggests that the way the brain executes the series of movements necessary to make sounds may prove to be the way the brain controls many of the body's activities. "[The findings] will have relevance to many aspects of human behavior," he predicts. If so, then the song of the zebra finch will indeed be music to the ears of neuroscientists.

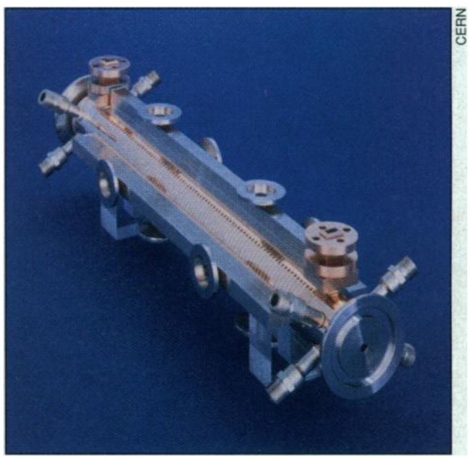
–Elizabeth Pennisi

PARTICLE PHYSICS

Politics Meets Technology in Next Collider

While the morale of the high-energy physicists, particularly in the United States, was severely dented by the cancellation of the U.S. Superconducting Super Collider (SSC) project in 1993, they did not dwell on that setback for long. Soon researchers were cooking up plans for an entirely new and truly international venture: the world's longest linear accelerator, or linac, which could stretch over a distance of 30 kilometers. And late last month, at the 18th International Linac Conference in Geneva, the giant linac took another step from pipe dream to reality, as five different physics groups unfurled blueprints for the machine.

This Next Linear Collider (NLC), as it's called, would not be the most powerful accelerator in the world; that honor will go to the Large Hadron Collider (LHC), soon to begin construction at CERN, the European particle physics laboratory near Geneva. But the unique properties of linear colliders should ensure new physics results to complement the



Fast track. Prototype high-frequency accelerating cavity at CERN.

findings from the LHC. The NLC also presents some unique technical challenges. And because the multibillion-dollar machine would be built as an international project at a site yet to be determined, the technical choices are bound up with political ones. "The goal is to look at these designs, and then to make some very difficult choices," says Tor Raubenheimer of the Stanford Linear Accelerator Center (SLAC) in California. "It will take about another year and a half to develop an actual proposal with actual monetary figures," adds

Wolfgang Panofsky, former director of SLAC.

In recent years, circular accelerators have reigned supreme in particle physics. Their main advantage is that particles circling the ring many times can get repeated boosts from the same set of accelerating cavities. There are drawbacks, however. Forcing the particles into a circular path causes them to shed energy in the form of "synchrotron radiation." These energy losses are extremely severe for light particles. An electron, for example, loses 10^{13} times as much energy this way as does a proton of the same energy. CERN's Large Electron-Positron Collider (LEP), currently the world's most powerful collider of leptons (light particles that include electrons and their antimatter twins, positrons), is expected to achieve a collision energy of 174 gigaelectron volts (GeV) in October, but physicists believe circular lepton colliders may be hitting a ceiling. "LEP is the practical limit of what can be achieved without unreasonable synchrotron losses," says Jean-Pierre Delahaye of CERN.

Circular accelerators can attain much higher energies by accelerating the heavier particles known as hadrons, which include protons. The LHC, for example, will be built in the same 27-kilometer tunnel that houses LEP and yet will be able to achieve collision energies tens of times higher—14,000 GeV, or 14 TeV. Physicists, however, still believe it is necessary to have a more powerful lepton collider than LEP. One reason is that hadrons are composite particles, made up of quarks and gluons, and hence their collisions are messy and complicated, which can make spotting rare and unusual events difficult. Leptons, on the other hand, are fundamental particles, and so their collisions are cleaner and easier to interpret.

Accelerating the leptons in a linear collider adds to those advantages. In circular colliders, the profusion of bending magnets and accelerating cavities and the beam's repeated passes around the ring make it hard to keep the beam narrow and well focused. In linacs, however, the beam makes only one pass and there are no bending magnets. The aim for the NLC is to have a beam between 3 and 30 nanometers across, more than 10,000 times finer than the LHC's beam. A finer beam means a much greater probability of collisions, again improving NLC's chances of spotting rare events. So the NLC will be a precision tool to LHC's jackhammer. "It is not an either-or situation; the two machines complement each other beautifully," says Gregory Loew of SLAC.

The current specifications for the NLC call for a pair of linacs facing off to collide particles with a total energy of 500 GeV. But as detailed by the five research teams now investigating designs—one at SLAC; one at CERN; two at DESY, the German particle physics lab near Hamburg; and one at KEK, Japan's National Laboratory for High-Energy Physics in Tsukuba—just how this will be done will affect the size, cost, and reliability of the machine.

NEXT LINEAR COLLIDER DESIGNS

Laboratory	Accelerator	Description
SLAC	Next Linear Collider Test Accelerator	11.4-gigahertz copper cavities, powered by klystrons
DESY	TESLA Test Accelerator	1.3-gigahertz superconducting cavities
	SBTA (S-Band Test Accelerator)	3-gigahertz copper cavities
KEK	JLC (Japan Linear Collider)	11.4-gigahertz copper cavities
CERN	CLIC (Compact Linear Collider)	30-gigahertz copper cavities powered by a drive linac with superconducting cavities

One of the key questions these teams have to answer is what type of accelerating cavity to use. Cavities are large metal cylinders into which are passed very powerful radio waves, with wavelengths between 3 and 30 centimeters. These waves resonate inside them like sound in an organ pipe. The electric field that accompanies these waves accelerates the particles as they pass through. Traditionally, the cavities have been made of copper, and the teams at SLAC, KEK, and one of those at DESY have all stuck with this tried and tested technology.

The second DESY team, however, has opted for superconducting cavities made of niobium and cooled with liquid helium to extremely low temperatures. In superconductors, the lack of electrical resistance makes power losses due to currents induced in the cavity walls negligible. "The power is almost entirely absorbed by the electron beam. You have an efficiency rate of nearly 100%," says Jörg Rossbach of DESY. Superconducting cavities work at lower frequencies than copper ones, making the cavities large and very expensive, but it is hoped that the expense will be offset by the lower operating costs.

Other groups have pursued a different cost-saving strategy: shortening the cavities, and hence the accelerator, by opting for higher frequency radio waves, which have shorter wavelengths. Existing linacs rely on klystrons, electron tubes in which a powerful "bunching" electron beam generates high-frequency signals that are fed into the accelerating cavities. The SLAC team already demonstrated a so-called X-band klystron and will stick with this arrangement in their design, which calls for 4500 klystrons sending 50-megawatt pulses to 9000 copper cavities (4500 for each linac).

But klystrons cannot generate radio waves with a frequency above 11.4 gigahertz and a wavelength shorter than 3 centimeters. The CERN team and a collaboration of the Lawrence Berkeley and Lawrence Livermore national laboratories are investigating an alternative strategy that would enable them to use a frequency as high as 30 gigahertz. Taking the place of the klystrons in this scheme is a low-energy drive linac running alongside the main linac. This linac runs in reverse: A high-current beam is accelerated by cavities, and other cavities in turn decelerate the beam, generating a radio signal that passes through waveguides to the accelerating cavities on the main linac. The resulting shorter wavelengths reduce the total length of the collider to less than 20 kilometers. The scheme has a major drawback, however: If the drive linac breaks down, the whole collider is out of action, says SLAC's Raubenheimer. In contrast, one failed klystron would not stop an accelerator of conventional design.

Political rather than technical considerations may drive the ultimate choice of accelerating scheme, however. "A linac of 30 or 40 kilometers may be much harder to get approved [in the United States] than a linac of 20 kilometers," explains Rossbach, adding, "In Japan this is also obvious, because real estate and civil engineering are [so] expensive. The optimization game leads to different results in different countries."

But perhaps the toughest decision for the coalition of scientists now working on NLC designs will be where to site it. Because the NLC will produce a much finer beam than existing accelerators do, ground stability becomes a key issue. "In Japan there is a suitable site on a granite slab, and there are other areas in the world that are rock-stable," says SLAC's Loew.

The complex technical and political issues surrounding the NLC, as well as its international nature, will undoubtedly make approval a difficult process. "This is a problem, because in principle one would like to decouple the technical decision from the political decision of the site," says Panofsky. But he believes physicists have learned from past mistakes that playing politics is as important as getting the science right. The NLC project will succeed, says former SLAC director Panofsky, "if we do a better job handling it than with the SSC."

–Alexander Hellemans

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