the sediments of shallow waters where mud low in oxygen is exposed to sunlight.

The things bacteria don't do mostly seem to be things the environment doesn't easily let them do. But although, as a group, bacteria can make use of more or less every reaction within thermodynamic and ecological limits, any given bacterium can probably only manage a few of them. Given the apparent ease with which bacteria and archaea swap genes, this might seem surprising. Why don't photosynthetic sulphur bacteria, for example, ever reduce sulphate in the dark? Why are different bacteria needed to oxidize ammonia to nitrate and then reduce the nitrate back to nitrogen. In short, why is there not one super-bacterium that does everything?

"That's a vexed question!" says Blankenship. "I'd say it was something to do with redox reactions running one way under some conditions, and another way if you change the conditions. So to make a certain reaction work, a bacterium has to occupy a particular niche." If a specific range of redox potentials are needed for some processes to work, but others are not compatible with that, then "the best solution is to cooperate with your neighbour", adds Blankenship. The ecosystem thus becomes a way of dealing with the build up of waste products, and getting as much energy as possible out of the environment.

If Blankenship is right, the immense subtlety with which bacteria are able to get one thing done may be what stops them from getting everything done. If they weren't constrained by their own fine tuning of redox conditions, there wouldn't be any diverse microbial systems.

And there's an obvious corollary. If you really want to understand how bacteria and archaea make their livings, you need to study communities, not individuals, whether they be tightly coupled partnerships such as those between archaea and bacteria that oxidize methane or the looser, more complex communities found wherever the redox potential of a sediment varies with depth. And that approach requires, among other things, a new culture of microbiology. As Nealson puts it: "When I was a student, you were thrown out for working with mixed cultures, but today the interest is in how bacterial consortia operate. If you fish out two bacteria in a cling, they're doing something together, but we've hardly begun to look." ■

Nick Lane is a science writer based in London.

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C. DARKIN

Circuits of slime

The left-hand side of Peter Girguis's lab is a mucky place. Dried mud flecks benches, beakers and scales, and buckets of slime clutter the floor. Fresh ooze is flown in regularly from California. A skein of pipes fed by a 2,000-gallon tank of sea water in the basement keeps everything moist. On the floor, wires gush out of dismembered plastic cocoons, and electrodes poke out of various tanks.

The messy workplace is a design shop for electrical generators. This summer, microbiologist Girguis and his colleagues at Harvard University in Cambridge, Massachusetts, will shove graphite electrodes, like those used in this lab, into the sea floor of Monterey Bay in California. The current that flows between the electrodes will power a suite of scientific instruments, including a wave and tide meter, and a fluorometer that measures levels of chlorophyll in sea water.

Girguis's work depends on the fact that when bacteria respire they pull electrons off organic debris. Catch those electrons on an electrode that is hooked up to a second electrode in free water, say, or in air, or in another layer of sediment where the microbes use a different sort of electrochemistry (see page 274) — and the electrons will flow from the first to the second electrode. That gives you a current with which you can power things.

The currents produced by these microbial fuel cells are small, but their potential, in the non-voltage sense, may be surprisingly large. After all, microbes can produce electrons from sediment, sewage, food scraps or pig slop. Girguis, a self-confessed gearhead, takes some delight in a simple demonstration of their current-generating abilities using just a bucket, some hardware-store supplies and a bag of cow manure.

People have been trying to harness the power of microbes in this way since the early 1900s, although with little practical success. Engineering advances and molecular biology's new tools, some of which have a home in the clean half of Giguis's lab, have allowed him and like-minded researchers to breathe life into the field.

"This technology would transform the world if it ever became reliable and could be used on a large scale," says Bruce Rittman, director of the Center for Environmental Biotechnology at Arizona State University's Biodesign Institute in Tempe. But he admits that is still a dream. "We are quite some distance from capturing the benefits at an economic scale." To get there, he estimates that researchers will need to produce fuel cells with power-generating abilities that are a hundred times greater than those of today's cells.

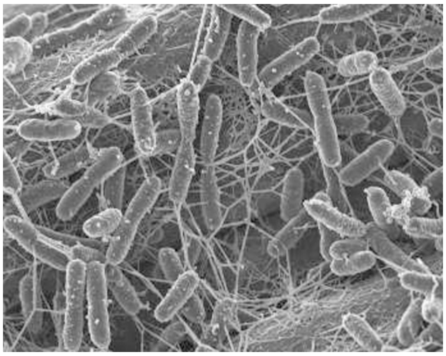
"All of microbial fuel-cell research invariably has to deal with the interface between microbes and the electrodes," says Girguis. One approach, favoured by engineers, is to try to improve the cell's design and the materials from which the electrodes are made. Biologists, however, aspire to better understand the microbes themselves, with the aim of informing more sophisticated designs — or designing better bacteria.

Natural lighting

Fuel-cell builders have been adding electron mediators — small molecules that help electrons move around — to their systems for years to increase the current. But another way to enhance performance may be to increase the physical contact between the bacteria and the electrodes.

Last year, Derek Lovley at the University of Massachusetts, Amherst, revealed that members of a group of bacteria called *Geobacter* extrude protein spines, or pili, which conduct electricity[2]. And they are not the only ones, according to findings presented this February at a conference sponsored by the US Department of Energy, and held in Bethesda, Maryland.

Yuri Gorby from the Pacific Northwest National Laboratory in Richland, Washington, reported that nanowires sprout from a range of bacteria, including the iron-breathing microbes *Shewanella* and the photosynthetic bacteria *Synechocystis*. Using *Synechocystis*, he and his colleagues have made a solar-powered form of microbial fuel cell. The key to the nanowires' conductivity, Gorby and his colleagues found, was the presence of certain cytochromes — electron-shuttling molecules found in bacterial membranes. Bacteria lacking the nanowires or cytochromes are poor conductors of electricity.



B. AREY/PNNL

Multi-talented: microbes could help remove toxins from waste water, and power the treatment plants.

Researchers are already thinking about how to harness the findings. Gorby's colleague, microbiologist Ken Nealson at the University of Southern California in Los Angeles, points out that *Geobacter* and *Shewanella* have evolved to transfer electrons to scraps of metal found in nature, not to an artificial electrode. Encouraging them to evolve electrode compatibility might yield a great deal of improvement. Nealson and Lovley say that 'electrode-adapted' bacteria could one day produce fuel cells with at least 100-fold greater power-generating abilities compared with current cells.

"This technology would transform the world if it ever became reliable and could be used on a large scale."
— Bruce Rittman

Such 'improved' bacteria might be too specialized and delicate to thrive in marine sediments. But they could be put to use in purpose-built closed bioreactor systems, where they could generate electricity by chewing up biomass. "It's the best approach we have to developing an industrial application or producing a lot of power," says Girguis.

While the biologists extol the potential of nanowires, Bruce Logan, an environmental engineer at the Pennsylvania State University in University Park, prefers to concentrate on the chemistry and physics of the fuel cells. Logan says he hasn't seen much practical advance from understanding the biology of the microbes. "It's not clear whether we are limited by the bacteria or the physics of the system," he says. And although he is not dismissive of the microbiologists — indeed he has just started collaborating with Nealson — he argues that "most of our improvements have been geared towards the physics and chemistry, suggesting that that is the major roadblock."

Energy on the cheap

Logan works with industrial runoff, animal waste and sewage. At least 1.5% of US electricity production goes into wastewater treatment, he says. He wants to change that equation, by developing systems that produce electricity as well as cleaning the water.

The field of wastewater treatment by fuel cells was opened up by Byung-Hong Kim, a microbiologist from the Korea Institute of Science and Technology in Seoul; Kim developed a system that didn't need added electron mediators in the 1990s[3]. Since then engineers, such as Logan, have worked on various ways of improving the design and the power output of these cells. Logan's most recent table-top device yields the equivalent of 15.5 watts per cubic metre of household waste water flowing through it[4].

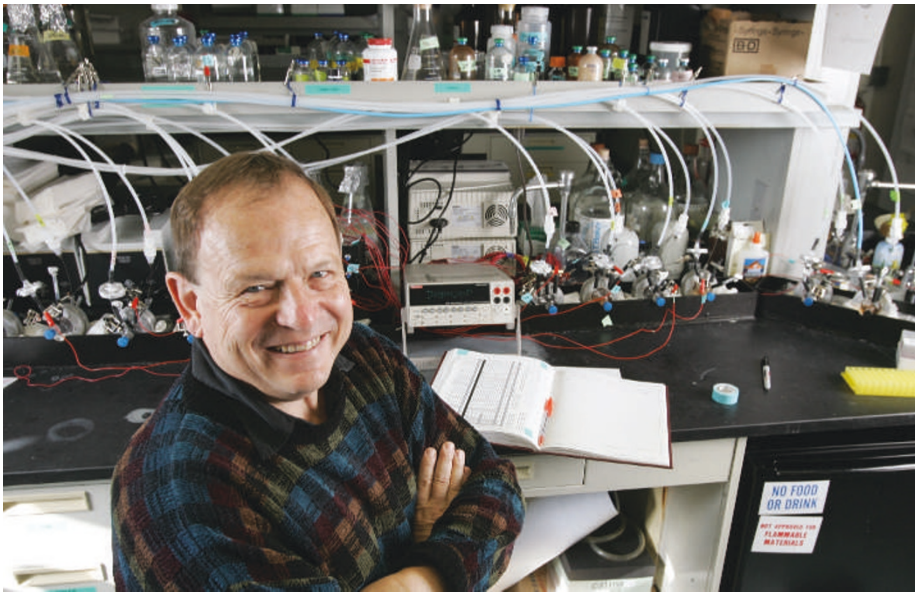
By the standards of a conventional fuel cell, such as one powered by hydrogen, that's a very poor yield. But with scale-up, Logan estimates that the waste water from 100,000 people, or a large industrial plant, could produce 0.8 megawatts, enough to power about 500 homes. Such a system would also scrub waste water of troublesome compounds such as ammonia, which is consumed by the microbes, and produce 50–90% less sludge than conventional methods.

Unfortunately, the electron-gathering anodes in Logan's laboratory systems are made from moderately expensive graphite or carbon paper, and the cathodes need to be coated with very costly platinum for the best effects. Willy Verstraete, an environmental engineer at Ghent University in Belgium, says that, extrapolating

P. GIRGUIS

The power of mud: soil bacteria free up electrons as they respire. When used to induce a current between electrodes, these can light up a lamp.

P. CHANNING/USC COLLEGE



Ken Nealson thinks technologies using microbes could be improved by knowing about their biology.

linearly from the costs of the prototypes, the capital expenditure for a full-scale plant would be five to ten times higher than it is for today's treatment plants. So the hunt is on for cheaper materials.

Logan points out that the technology does not have to be cheap, just cheaper than the current techniques. The United States already spends about $25 billion each year on domestic wastewater treatment, he says. He is working on a design of fuel cell that he says could be cost effective and scalable; he hopes this will yield ten times as much power per cubic metre of waste water as current designs do.

Power to the people

Verstraete is more cautious. "Industry is expressing a lot of interest," he says, "but they are not putting the money on the table." He says that companies want to see yields as high as 1,000 watts per cubic metre — and to see them in prototypes a thousand times larger than the milk-carton-sized devices now honing the technology. He sees a role for the technology in cleaning certain nitrogenous pollutants out of waste water, or chewing up effluents from the digesters that convert biomass to methane on some farms. But it's still a long road to the first microbial car (see 'And what if it worked?').

Meanwhile, the powering of marine instruments seems to be the application moving the fastest. Girguis's work on Monterey Bay sediments follows the lead of pioneers such as Lenny Tender at the US Naval Research Laboratory in Washington DC. Tender was one of the team that first successfully extracted current from marine sediment more than five years ago[5]. This summer, Tender plans to launch a microbial fuel cell that powers an acoustic device for measuring water velocity. Taking measurements every 4 hours it will consume an average of just 0.1 watts.

Environmental monitoring on the land and the ocean surface is increasingly powered by solar cells that can work for years unsupervised. The ocean floors, being abysmally short of sunlight, need a different approach, and Tender, Girguis and their colleagues think that microbial-powered electricity is the solution. This would obviate the need for battery replacement that currently drives up the costs of such studies.

"They have a lot more work to do before they can call this a real proven technology," says James Bellingham, chief technologist at the Monterey Bay Aquarium Research Institute, who is working with Girguis. "But these guys have come very far very fast."

Which other niche areas might be successful is less clear. For his terrestrial applications, Girguis is collaborating with an architect who specializes in new materials. Together, they plan to design LED lighting systems that can be powered by a bucket of food scraps or animal waste. He says such devices could be mass-produced for about ten dollars each and could help generate light for many of the 1.6 billion people living outside the world's electrical grid. Although such people are obvious candidates for solar power, Giguis says the microbial option has the advantage of being much less expensive to manufacture and easier to operate and repair. And it can work in the dark.

The technology need not always be cheap and cheerful. Rittman has a grant of $100,000 from NASA to design a compact microbial fuel cell that consumes human waste during a manned astronaut mission. But like many researchers in the area, he dreams of bigger opportunities on Earth. If microbial fuel cells could be adapted for the consumption of plant biomass, they could in theory produce twice the amount of electrical energy that combustion-driven generators can, says Rittman. Again, however, the best that has been done is not quite that good, and is stuck on the lab bench for now.

But Nealson, for one, is confident things can improve, especially if links between different disciplines housed in different departments can be strengthened. "Our job here is to understand how the bacteria work, and once we know that we can get together with the engineers. Then you might find out how to make the ideal fuel cell." He laughs, "maybe it will drive itself across campus." ■

Charlotte Schubert is senior News and Views editor for *Nature Medicine*

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AND WHAT IF IT WORKED?

In his satirical novel *Distraction*, science-fiction author Bruce Sterling imagines the development of a microbial power source for future cars — and the industry's fear of the far-reaching changes it heralds. Here, one of his characters rails against the hapless innovator:

"You think it's easy running corporate R&D? It was just fine, as long as the guy didn't have anything. Jesus, nobody ever thought a goddamn sugar engine would work. The goddamn thing is just a germ in a box! We build cars up here, we don't build giant germs! Then they pull this crazy stunt and... well it makes our life impossible! We're a classic metal bending industry! We have interlocking directorates all throughout the structure, raw materials, fuel, spare parts, the dealerships... We can't get into the face of our fuel suppliers, telling them that we're replacing them with sugar water! We own our fuel suppliers! It'd be like sawing off our own foot!

"Batteries have the highest profit margin of any automobile component. We were making money there. You can't make real money anywhere else in our business. The Koreans are building auto bodies out of straw and paper! We can't support an industry when cars are cheaper than grocery carts! What are we going to tell the unions? This is a great American tradition at stake here! The car defines America: the assembly line, suburbs, drive-ins, hot rods, teenage sex, everything that makes America great! We can't turn ourselves inside out because some big-brained creep has built an engine out of bug guts! There wouldn't be anything left of us! The guy is a menace to society! He had to be stopped."