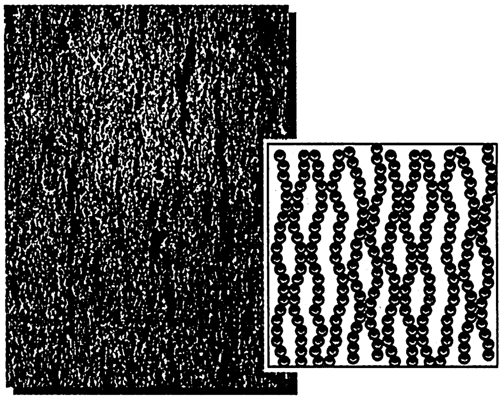

Power lines. Conducting particles aligned by a magnetic field offer sharp warnings of changes that break their connections.

dering of carbon particles, Martin says.

Martin suspected that researchers could make the sensors more sensitive and reliable by stringing the conducting particles between the electrodes like tiny wires. In that arrangement even slight environmental changes would change the polymer enough to knock the particle chains out of alignment. To get that alignment, Martin's team decided to use a magnetic field, which causes magnetic particles to line up in the direction of the field lines (see figure at left). Because carbon particles aren't magnetic, the Sandia researchers used nickel particles, each about 2 millionths of a meter across. They electroplated each particle with a thin layer of gold to prevent the nickel from oxidizing when exposed to air, a change that would destroy the particle's conductivity. They then embedded their gold-coated nickel particles in an uncured polymer and exposed the combo to an external magnetic field. Once the particles were aligned in chains, the researchers cured the polymer and began their tests.

The results were dramatic. Bumping up the temperature just 5 degrees Celsius slashed the electrical resistance by five orders of magnitude. An 80-degree change made it plummet by 10 orders of magnitude. Modest pressure changes produced an effect of 11 orders of magnitude. And even exposing the polymer to a chemical vapor of toluene caused the polymer to expand and altered the resistance by nine orders of magnitude. "We were surprised by how well it worked," Martin says.

Martin says he has no immediate plans to commercialize the materials: "We're still at the level of science." Some bugs still remain to be ironed out as well. For example, many of the particles oxidize over time when exposed to air, probably a result of incomplete electroplating. But once the composites are fine-tuned, they are likely to be a hot commercial property, Christenson predicts.

–ROBERT F. SERVICE

PLANT BIOTECHNOLOGY

For Plants, Reproduction Without Sex May Be Better

A better understanding of how plants reproduce asexually by apomixis may boost efforts to develop improved crops

Mention embryo formation, and thoughts usually turn to sex: the union of sperm and egg to produce a new individual. But several common plants, including dandelion, citrus, mango, and certain forage grasses, can do without sex, producing their embryos from unfertilized immature sex cells or even from ordinary somatic cells. Although plant biologists have known about this bizarre form of reproduction, called apomixis, for about a century, only recently have they begun to get a glimmer of insight into how plants achieve the feat.

Within the past few years, researchers have identified a variety of genes that may determine whether plants reproduce sexually or asexually by apomixis. Eventually, they hope to use these genes to develop new strains of apomictic crop plants. The payoff could be enormous. Because the progeny of apomixis are identical to the parents, traits transferred into an apomictic plant, whether by classical breeding or genetic engineering, wouldn't be lost in the genetic shuffling that occurs during sexual reproduction.

Apomixis also offers a possible way to avoid the degeneration of breeding stocks of some vegetatively propagated plants, such as potato and cassava, that accumulate pathogens through repeated use. "Apomixis could play a major role in feeding the growing population of our planet," says plant developmental biologist Ueli Grossniklaus of the University of Zürich, Switzerland. "It could promise social and economic benefits that would challenge those of the Green Revolution." As a result, "apomixis is a very, very hot area of research," says Robert Goldberg, a plant biologist at the University of California, Los Angeles.

Funding agencies are beginning to pay attention. In 2001, for example, the ApoTool European Union funded the $2 million program, coordinated by Sacco de Vries of the University of Wageningen in the Netherlands, to further the identification of genes that might go into a custom-designed apomict. In addition, the International Maize and Wheat Improvement Center in Mexico and various funding agencies in the United States—including the Department of Agriculture (USDA), the National Science Foundation, the Department of Energy, and the Rockefeller Foundation—are providing modest, but increasing, support for the research. And several biotech companies—such as Ceres of Malibu, California, which was cofounded by Goldberg, and Apomyx of North Logan, Utah—have research efforts devoted to apomixis, although they are keeping quiet about the number of dollars invested.

A measure of this increased worldwide interest was evident at last April's XVIth International Congress on Sexual Plant Reproduction in Banff, Canada, where 170 people signed up for the apomixis section alone. At the previous meeting, 2 years earlier, just 140 scientists had attended the entire meeting.

A long slog. This corn-gamagrass hybrid was one of many produced on way to an apomictic corn strain.

One development that helped spark this interest came in 1998 when two teams of classical plant breeders, working independently, demonstrated the feasibility of introducing the apomixis trait into crop plants that normally reproduce sexually. Bryan Kindiger, Phillip Sims, and Chet Dewald of the USDA's Agricultural Research Service (ARS) Southern Plains Range Research Station in Woodward, Oklahoma, developed corn that reproduces by apomixis by crossing the grain with an apomictic relative, eastern gamagrass (*Tripsacum dactyloides*). Their success didn't come easily.

The team had to perform at

CREDITS: (TOP TO BOTTOM) J. MARTIN/SANDIA NATIONAL LABORATORIES; KEN HAMMOND/USDA least 5000 backcrosses to get a fertile grass-corn hybrid and thousands more crosses to get apomictic corn. "It was a long haul, a difficult and elusive challenge," says Dewald, whose team worked on the project for nearly 20 years. After a similarly long slog, Wayne Hanna and his colleagues at the ARS Coastal Plains Research Station in Tifton, Georgia, transferred apomictic genes from the forage grass *Pennisetum squamulatum* to its cultivated relative, pearl millet, a popular birdseed.

So far, the new corn and millet apomicts aren't fertile enough for commercial application, but fertility is improving. "We've gone from having 4% or 5% fertility in corn to about 10%, but we're still a long way from a commercial crop," says Dewald, who adds that 80% fertility would be a desirable first goal for a commercial cultivar.

Despite these successes, conventional breeding of new apomicts faces a big obstacle: Few valuable food plants have close apomictic relatives that can be used for crossbreeding. To get around this, plant researchers are hoping to engineer an apomictic plant. They are trying to identify mutations of genes coding for key steps in sexual development that could produce a form of apomixis when transferred into other species. "I think it can be done with the newer, molecular tools," says Dewald, who began breeding natural forage apomicts some years before molecular tools became available.

As in much of plant genetics these days, the search is focusing on the model plant *Arabidopsis thaliana*. In recent years, researchers have identified hundreds of mutations in *Arabidopsis* and a few other plants that affect embryo development. And they have found that the products of some of these genes can elicit embryo formation from the vegetative tissue of *Arabidopsis*. In 1998, for example, Goldberg—with John Harada of the University of California, Davis; Bob Fischer of UC Berkeley; and their colleagues—cloned a gene called *LEAFY COTYLEDON 1* (*LEC1*). The researchers showed that the gene, which was already known to be involved in embryo formation, can trigger the formation of embryolike structures when it is expressed in leaves.

Last August, the same team described a second gene, *LEAFY COTYLEDON 2* (*LEC2*), with similar activity. And in unpublished work, Kim Boutilier of Plant Research International, a nonprofit research institute in Wageningen, cloned the *BABY BOOM* gene from canola (*Brassica napus*) and showed that when that gene is expressed in *Arabidopsis* it has an even more dramatic effect than *LEC1*, leading to the production of hundreds of embryos on seedlings. The group has applied for a patent on the gene.

The proteins produced by the *LEC* and *BABY BOOM* genes are thought to regulate gene activity directly, but genes that make other types of proteins can also enhance the production of embryos from somatic cells. One example, found this year by De Vries, is a gene called *SERK* (for somatic embryogenesis receptor kinase) that increases sensitivity to growth-inducing compounds, such as plant hormones.

Getting embryos to form is only half the battle in producing viable seed, however. Conventional seed formation requires two fertilizations, one of the egg, which yields the embryo, and another of the so-called central cell that goes on to make the endosperm that nourishes the embryo. As a result, apomixis researchers are also focusing on isolating the genes involved in endosperm development.

In the late 1990s, three groups—one including Goldberg, Harada, and Fischer; another led by Zürich's Grossniklaus; and the third led by Abdul Chaudhury of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Canberra, Australia—described mutations in three genes that lead to formation of endosperm and partial seeds in the absence of fertilization. All three genes, called *FERTILIZATION-INDEPENDENT ENDOSPERM* (*FIE*), *FERTILIZATION-INDEPENDENT SEED* (*FIS2*) and *MEDEA*, encode polycomb proteins, similar to polypeptides found in the fruit fly, mouse, and other species that are associated with condensed chromatin and repression of gene expression.

A typical apomict. The dandelions that proliferate in your lawn can do so without the aid of sexual reproduction.

CREDIT: SACCO DE VRIES

About a year ago, Rod Scott of the University of Bath, U.K., Hugh Dickinson of the University of Oxford, U.K., Fischer, and their colleagues extended this work. They showed that reducing DNA methylation, which can be achieved by means of mutations in any of several genes, improves endosperm development in *FIE* mutants.

Meanwhile, a few researchers are taking a very different tack to identify genes that might be used to engineer apomicts: Instead of looking for genes that influence seed development in *Arabidopsis*, they are probing select apomicts to see if they can find the genes involved in this asexual reproduction. For example, Peggy Ozias-Akins of the University of Georgia, Tifton, is studying *Pennisetum*, grasses related to millet; Ross Bicknell of Crop and Food Research Ltd., a government-sponsored company in Christchurch, New Zealand, and Anna Koltunow of CSIRO in Adelaide, Australia, are studying the dandelion relative *Hieracium aurantiacum*. Bicknell notes that this work is still in the very early stages and accounts for only 10% to 20% of all funds devoted to apomixis research. Indeed, he says, "we exist as the lunatic fringe of apomixis research."

Still, Bicknell cites some progress. A few years ago, his team identified a mutant form of *Hieracium* that had lost the ability to reproduce by apomixis and used ordinary sexual reproduction instead. Since then, he and his colleagues have discovered more than 80 such mutants. By comparing their gene expression profiles with those of plants that are naturally apomictic or sexual, the researchers hope to identify regulatory pathways that are critical for apomixis. Bicknell says they have already picked up several genes that seem to be important, although he declines to offer details, because the work was done under contract to Ceres and the genes may be patented.

Not everyone thinks that tinkering with a few or even generous clusters of genes will be enough to make apomicts, however. These researchers note that classical breeding programs had to add at least one complete alien chromosome, and often more, to transfer the desired trait into new species. John Carman, a plant evolutionary biologist at Utah State University in Logan, goes so far as to claim that "apomixis genes [per se] don't exist." Instead, he suggests, the process likely involves many genes located at different places in the genome that influence traits such as the timing of flower and embryo development. Even apomixis researcher Goldberg describes the study of apomixis as "far more daunting than the study of parthenogenesis in animals."

Nevertheless, what researchers have learned so far has raised their hopes. "The versatility of reproductive systems and the variability in known apomicts suggest that apomixis can be engineered," predicts Grossniklaus—even though the plant engineers' approach may not be the same as Mother Nature's. **–ANNE SIMON MOFFAT**

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