Gene Research Flowers in *Arabidopsis thaliana*

A scant 6 years ago, even plant biologists weren't paying much attention to the mustard-like plant called *Arabidopsis thaliana*. But since then this small plant—a full-grown specimen measures only about 30 centimeters—has become the model of choice for investigators who want to uncover the basic biochemical and genetic mysteries of plant life. Indeed, the growth of information about *Arabidopsis* is "exploding," according to a recent report from the National Science Foundation.* And one area in which the plant is proving especially valuable is the identification of the genes that regulate complex growth and developmental pathways in plants.

These regulatory genes are helping to fill a major information gap in plant biology. For while researchers have isolated dozens of plant genes, most have been the sort that specify relatively simple traits, such as herbicide resistance, or they are so-called housekeeping genes that make enzymes or other proteins needed for the day-to-day operations of the plant cell (also see p. 1581). They've had a much tougher time getting their hands on the genes that serve as "master switches" in plants, regulating whole batteries of subsidiary genes needed for plant development.

But now, with a big boost from *Arabidopsis*, that's begun to change, as illustrated by a flurry of recent reports, including two in this issue that describe new developmental mutants in *Arabidopsis*. While researchers are far from having a complete picture of the interplay of genes needed to make a plant, they have identified a series of genes that first act to establish the body plan of the developing *Arabidopsis* embryo and then determine the formation of the plant's specific tissues and organs, such as flowers, as well as the assembly of the basic machinery the plant uses to respond to light.


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Center of attention. *Arabidopsis* is shown here at about one-quarter of life size.

The hope is, the researchers say, that the *Arabidopsis* work will lead to the identification of comparable developmental control genes in other, economically important plants, much as the discovery of the "homeobox" genes that help regulate development in the fruit fly *Drosophila melanogaster* led to the identification of the mammalian homeobox genes. Ultimately, the information gleaned from *Arabidopsis* might be used to increase plant productivity, by aiding, for example, in the development of new plant strains that flower earlier, give fruits and seeds more time to develop, or that grow more efficiently in response to light. And along the way, *Arabidopsis* is teaching biologists that while in some developmental aspects plants are similar to animals, in others they may be quite different.

One problem that's handicapped the search for master regulatory genes in plants in the past is the complexity of the pathways they control, says developmental biologist Scott Poethig of the University of Pennsylvania. If a defect turns up in a flower, say, it's necessary to sort out whether a high-ranking regulatory gene —rather than one of the many genes under its control—is at fault. As Poethig points out, it's a real challenge "to relate problems of growth and differentiation to errors of regulation." To do so, investigators have to generate many different mutants, screen for interesting ones, and then see how their effects play out over several generations. Animal geneticists could use their own favorite creature for these experiments—the rapidly maturing and highly prolific fruit fly. But comparable experiments weren't practical with plants, which can take months or years to reach maturity and have extremely complicated genomes to boot.

And that's where *Arabidopsis* is proving to be such a boon. Indeed, it's becoming the fruit fly of the plant world. Because *Arabidopsis* plants are so small, tens of thousands can be grown in the lab at one time. And they grow very fast; it takes only 5 to 6 weeks to go from the seed to the mature plant. The plants are also unusually prolific, each producing thousands of seeds. What's more, the *Arabidopsis* genome is relatively small: At about 100,000 kilobases, it's roughly the same size as the fruit fly genome. Says Gerry Fink, director of the Whitehead Institute in Cambridge, Massachusetts, and a yeast geneticist who has turned over part of his lab to *Arabidopsis* studies, "Plants have enormously interesting physiology, and using *Arabidopsis* as a model plant, many classic problems can be pulled apart, even in small labs."

One principle emerging from this "pulling apart" is that in some ways embryonic development in *Arabidopsis* resembles that in the fruit fly. Take, for example, results obtained over the past few years by geneticist Gerd Jürgens of the University of Munich and his colleagues. They have so far identified nine genes, out of an estimated 30 to 40, that direct the overall organization of the plant embryo. Some of these genes seem to establish the longitudinal axis of the plant from the tip of the shoot to the tip of the root, while others set up the cross-sectional or radial axis. And, says Jürgens, that's not unlike what happens in fruit fly embryos, where various sets of genes cooperate to set up the head-to-tail and dorsal-ventral axes.

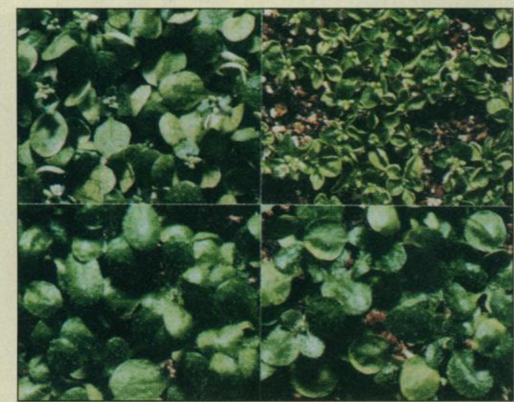
Once the body plan of the *Arabidopsis* embryo is established, other regulatory genes come into play to specify the formation of the various plant organs. A dozen or so groups are looking at these genes. One of the areas in which the work is most advanced is the identification of the genes that control flower development. And here, too, there are some key parallels between master regulatory genes in plants and animals, says geneticist Elliot Meyerowitz of the California Institute of Technology, whose team has identified four genes in three classes that specify organ type in flowers.

One point of resemblance is in the way these genes interact to control the formation of the various flower parts. "When these genes function correctly," says Meyerowitz, "they talk to each other, acting to turn each other on and off." This communication sets up a precise pattern of gene activity, with the genes being switched on and off at just the right times and places in the floral meristem, the part of the plant that produces flowers. The mutants the Caltech group has found show what happens when the pattern is disturbed. The flower petals become stamens, for example, or stamens become carpels. These kinds of mutations, in which a normal body part is found in the wrong place, are known

*"The Multinational Coordinated *Arabidopsis thaliana* Genome Research Project, Progress Report: Year Two."

'Housekeeping' Genes May Have Biotech Applications

Because regulatory genes are the executive staff of the plant genome, directing overall operations, they are considered prized trophies for the few researchers who have so far captured any (see main story). But *Arabidopsis* is also proving to be fertile ground for plant molecular biologists who study the more ordinary "housekeeping genes" that take care of the plant's everyday needs. Spurring the work is the evidence that some of these housekeeping genes have potential applications in the plant biotech industry, as a few current examples show.



Susceptible. Mutant *Arabidopsis* plants with defective flavonoid synthesis *(right)* are more affected by UVB light *(upper panels)* than wild type plants.

■ A team led by Chris Somerville of Michigan State University in East Lansing recently cloned the *Arabidopsis* gene for the enzyme omega-3-desaturase (*Science*, 20 November, p. 1353). The enzyme's job is to help synthesize "polyunsaturated" fatty acids—those which have multiple double bonds—by putting a double bond between carbons three and four of the fatty acid chain. Plant genetic engineers might be able to manipulate the gene to create new plant strains that make more polyunsaturated fatty acids, which are considered desirable from a nutritional point of view because they help lower blood cholesterol, although they also go rancid quickly. And because the polyunsaturated fats solidify less readily at low temperatures than their more saturated counterparts, such plants might be more cold hardy.

■ Robert Last and his colleagues at the Boyce Thompson Institute for Plant Research in Ithaca, New York, have found that mutations in the *Arabidopsis* genes for two enzymes, chalcone synthase and chalcone isomerase, leave the host plant much more vulnerable to damage from ultraviolet (UV) light than its normal counterparts. (They report their findings in a forthcoming issue of *The Plant Cell*). As a result of the mutations, the plants lack UV light-absorbing compounds known as flavonoids, which are synthesized by the enzymes. Genetic engineers might be able to use the genes, Last suggests, to create plants that produce flavonoids more efficiently—and thus gain extra protection from the increased ultraviolet radiation passing through a thinning ozone layer.

■ And on page 1654, a team from Northwestern University and the Davis and San Diego campuses of the University of California report that an *Arabidopsis* gene they cloned earlier encodes an ion channel known as the inward rectifying potassium channel. In plants, this sort of channel, which regulates the movement of potassium ions into the cell, influences the closing of the stomates, the tiny pores that regulate the movements of water and gases, such as oxygen and carbon dioxide, into and out of leaves. The animal counterpart of the channel helps regulate key physiological activities such as heart rate. While the *Arabidopsis* gene, which is called *KAT1*, has no immediate biotech applications on its own, it is possible to create a model system for studying the channel by transferring the gene into yeast, says the team leader, Northwestern's Richard Gaber.

–A.S.M.

as "homoeotic" and have their counterpart in the homoeotic mutations of the fruit fly.

Another point of resemblance is that the recent cloning of some of the *Arabidopsis* homoeotic flower genes by Meyerowitz's group and former Meyerowitz postdoc Martin Yanofsky and his colleagues at the University of California, San Diego (reported in the 19 November issue of *Nature*), reveals that they, like fruit fly homoeotic genes, apparently encode transcription factors—proteins that regulate gene expression.

The two new *Arabidopsis* mutations reported in this issue show that plant-animal resemblances go only so far, however. One of these, described on page 1647 by David Meinke of Oklahoma State University in Stillwater, has some features of a homoeotic mutation, although it may not be totally "classic." It appears to affect a regulatory gene that functions late in embryonic development. And while this mutation causes several abnormalities, its most striking feature is that the embryos produce foliage leaves where they should have the embryonic leaves known as cotyledons.

The other mutation, described on page 1645, is not homoeotic, says Z. Rene Sung of the University of California, Berkeley, the leader of the team that found it. Instead of having normal organs in the wrong place, the mutant plants seem to skip a stage in embryonic development so that they bypass the production of ordinary vegetative shoots and produce flowers right away. The tiny mutant plantlets have clusters of immature flowers even as they emerge from the soil, Sung says.

The point of differences with animals is that despite the loss of what appear to be key developmental genes, both mutant plants can produce mature, albeit abnormal, plants that reproduce themselves. In contrast, similar mutations in a fruit fly might well be lethal, Meyerowitz says.

Another possible contrast between plant and animal regulatory genes emerged when Xing-Wang Deng of Yale University, Peter Quail at the U.S. Department of Agriculture's Plant Gene Expression Center in Albany, California, and their colleagues at the University of Arizona in Tucson cloned and sequenced a gene that acts as a master switch for turning on the operation of the plant's light response machinery, including the chloroplasts, the tiny subcellular structures that carry out photosynthesis. And it seems to operate by an unusual mechanism, the researchers report in the 27 November *Cell*.

The sequence reveals that it has both a zinc-binding motif, characteristic of a transcription factor that binds DNA in the nucleus, and a region similar in sequence to one of the G proteins, which are involved in transmitting signals picked up at the cell membrane and carried into the interior of the cell. This could mean that the protein produced by a regulatory gene does double duty, functioning in both picking up signals and getting them into the nucleus.

All of which should show biologists that plant cells are much more than animal cells with chloroplasts encased in wood: They have some novel tales to tell about basic biology. As the researchers might say: Let a thousand—*Arabidopsis*—flowers bloom.

–Anne Simon Moffat

Additional Reading

E. S. Cohen and E. M. Meyerowitz, "The War of the Whorls: Genetic Interactions Controlling Flower Development," *Nature* 353, 31 (1991.)

U. Mayer *et al.*, "Mutations Affecting Body Organization in the *Arabidopsis* Embryo," *ibid.*, p. 402.