Reply

Our review (Coen and Carpenter, 1993) describes how both the similarities and differences between flowers and shoots can be explained by the action of a set of genes modifying a common growth plan. This does not imply that flowers and shoots are directly derived from one another or that they serve the same function or that they express all of the same genes.

We would also like to point out that it is very misleading to claim that Goethe denied sexuality in plants because it did not fit with his theory. He only came to seriously question sexuality in plants 14 years after publication of his theory of metamorphosis after a conversation with F.J. Schelver. On hearing Schelver's doubts about the theory of sexuality, Goethe (1820) was surprised: "In my mature studies I had religiously accepted the dogma of sexuality in plants and was, therefore, taken aback now to hear a concept directly opposed to my own."

It is clear that Goethe, quite correctly, did not feel that sexuality in plants was incompatible with his theory of metamorphosis even though he was later attracted by Schelver's new scheme. "Accustomed as I had always been to preserve complete flexibility in my application of metamorphosis, I likewise found this [Schelver's] viewpoint not uncomfortable, although at the same time I could not immediately relinquish the other" (Goethe, 1820).

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Planting Ideas in the Schools

Rapid-cycling *Brassica rapa* plants—spindly, nondescript, with bright yellow flowers—may not look like agents of dramatic change, but in classrooms across the nation and abroad they are a potent tool in a concerted effort to revolutionize the way science is taught. The speed of their reproductive cycle and the ease with which they can be grown makes these plants ideal for use in the "hands-on," "inquiry-based" approaches to teaching science that are being adopted by more and more teachers and school systems. Such approaches allow students to actually carry out scientific investigations instead of learning scientific facts by rote memorization, which has become an all-too-common method of teaching science.

The rapid-cycling Brassicas, or "Fast Plants," embody another revolution in science education as well: partnerships between scientists and teachers in which scientists develop new curriculum ideas and educate teachers about how science is actually done, and in which teachers educate scientists about what kinds of inquiry are possible or appropriate for children. Such partnerships are widely viewed as essential if today's children are to grow into tomorrow's scientifically literate adults.

Fast Plants grew out of the attempts of Paul Williams, a plant pathologist at the University of Wisconsin, Madison, to breed rapid-cycling populations of several Brassica species to enhance research into the basic properties of this economically important genus (Williams and Hill, 1986). By plucking out the fastest growers of each species from among thousands of Brassica accessions in the USDA's National Plant Germplasm System and continuously interbreeding the fastest plants within each species, Williams and his collaborators were able to develop populations that reproduced rapidly and fairly synchronously but were otherwise heterogeneous. For instance, the *Brassica rapa* population flowered within 14 days and went from seed to seed in just 35 days, with no requirement for desiccation or dormancy, a feat unequaled even by Arabidopsis.

The properties of the rapid-cycling Brassicas—not only their compressed life cycle but also their size, hardiness, and ease of growth—prompted Williams to explore their potential as teaching tools. With a grant from the National Science Foundation (NSF) and in collaboration with

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teachers in the Madison area, he developed a set of educational materials using the plants, and he established the Wisconsin Fast Plants organization to make these materials and other information about the plants available. Knowing the financial burdens faced by many school districts, Williams and his colleagues designed the materials to be as inexpensive as possible: for example, the plants can be grown in plastic soda bottles or film canisters, and light banks can be constructed fairly easily from discarded lumber.

Although the Wisconsin Fast Plants organization produces its own educational materials and serves as a resource for teachers using the plants (detailed files of information about the plants in general and about particular genetic stocks are even available on a Gopher server connected to the Internet), Fast Plants have also been incorporated into the hands-on curricula designed by other organizations, including the National Science Resources Center, which is a joint project of the National Academy of Sciences and the Smithsonian Institution, and the National Gardening Association. By anyone's measure, Fast Plants have caught on. For many school districts, Fast Plants represent the first time they have been able to use plants successfully in the classroom, and Williams estimates conservatively that over a million students grew them last year.

A Plant for All Ages

What makes Fast Plants unusual among materials for teaching biology is that they can be used by students at any level. For younger children, it is enough just to plant the seeds and observe the way they change from day to day. Simply tending to their own plants gives children a sense of ownership and responsibility, and, especially for inner-city children who have never seen a garden, the ability to preside over a plant's growth can be a revelation. And because the plants are self-incompatible and must be pollinated by hand, using "bee-sticks," children become actively involved in their growth and reproduction.

Slightly older children (grade 6 in the National Science Resources Center curriculum) can carry out simple experiments with the plants, investigating some of the "hows" of biology in a way that is rarely possible with animals. For example, they can dissect flowers and seeds, observe tropisms, and examine the effects on plant growth of environmental influences such as light, water, nutrition, and chemicals. These kinds of experiments allow children to experience science for themselves: they can use their own knowledge of the world to predict the results of their experiments, or even to come up with the questions they wish to explore. And because many Brassica species are common food plants, the Fast Plants can help place biology in a context that is familiar to children—and, therefore, both more educational and less threatening than the abstract scientific concepts they are frequently taught.

As impressive as Fast Plants are for teaching biological concepts to elementary and middle school children, they have also turned out to be ideal for high school and college students, for whom the plants can illuminate what are otherwise often dry botanical concepts. For example, when Susan Singer discusses the angiosperm life cycle in her botany lectures at Carleton College, she grows Fast Plants and has her students refer to them. In fact, the plants can be used to teach not just botany but also basic biology—after all, as Carl McDaniel, whose introductory biology students at Rensselaer use Fast Plants exclusively, points out, plants are just as much living systems as animals, but they are much less problematical (and less expensive) to work with.

The rapid growth of the plants can transform laboratory classes dramatically. For instance, Philip Reid, a plant biologist at Smith College, was able to switch from a more traditional plant physiology class format to one that focuses on independent research projects. Similarly, McDaniel's introductory biology students no longer conduct "cookbook" labs that focus eac week on a different organism; insteac they observe the growth of the plants, cor duct simple experiments, and embark o their own research projects, all of whic give them first-hand experience in scienc as well as imparting actual scientific cor cepts. In fact, because the plants are s useful for visualizing genetic and biolog cal concepts, they may break down som of the barriers contributing to the balkan zation of biology. For instance, Rei reports that Fast Plants are now bein used in a Smith College genetics clas that had formerly relied solely on Drosopł ila and microbes to illustrate geneti principles.

Fast Plants can obviously be used nc only to teach basic botany or biology t high school and college level students bı also for sophisticated experiments i areas such as ecology, physiology, an genetics. Such experiments are possibl in part because Williams and his co leagues have identified and assemble a large number of genetic variants. Thes include nuclear and cytoplasmic male sterile lines, a gibberellin-responsiv dwarf mutant, a gibberellin-overproducin elongated internode mutant, pigmentatio mutants, chlorophyll mutants, and variant in quantitative traits such as hairines Moreover, the plants are able to serve a hosts for a number of crucifer pathogen In fact, Fast Plants are also ideal for man kinds of basic research— the purpose fc which they were originally developed- although as yet they are not being use as widely as many other model plants

Dissemination Is the Key

Although innovative teaching tools suc as the Fast Plants are essential if pr college science education is to be mac more meaningful, such tools are of us only if teachers are trained in how to us them effectively. To accomplish this, tł staff of the Wisconsin Fast Plants orgar zation, with substantial support from tł NSF, conducts workshops in which not o ly teachers but also science educators (e.g., from museums) and scientists are trained to use the plants. At least one scientific society, the American Society of Plant Physiologists, has sponsored Fast Plants workshops for its members. Once they have received training, many people not only use the plants in their own teaching but go on to lead teacher training workshops in their communities.

These subsequent workshops not only serve as an amplification step, helping bring Fast Plants into more schools, but also lead frequently to closer ties between scientists and universities, on the one hand, and teachers and school districts, on the other. For example, Mary Musgrave, a plant physiologist at Louisiana State University who has led a number of teacher workshops, finds that through these workshops, teachers gain a sense that university scientists are approachable and are interested in them. In her workshops, which are attended mainly by teachers of underrepresented minorities, Maria Elena Zavala of California State University–Northridge often talks not only about how to grow and use the plants but also about herself and her experiences in science.

Musgrave points out further that in providing a ready-made package for scientists to do teacher outreach, Fast Plants give scientists a way to become personally involved in influencing precollege education. This aspect of the Fast Plants is certainly not unique—individual scientists have long contributed significant time and effort to local schools—but Fast Plants are part of a trend toward a more systematic and large-scale implementation of scientist involvement in K–12 science education. Earlier this year, for example, the NSF awarded nearly $4 million to the Carnegie Institution of Washington to create an academy in which scientists and educators will provide Washington, DC–area teachers with in-depth training in a variety of hands-on teaching tools and methods. Another large grant, to the American Chemical Society, will be used to fund the training of elementary and middle-school chemistry teachers by teams of scientists, teachers, and educators. And numerous smaller grants fund projects that bring teachers to universities, zoos, or science museums to learn about everything from insect behavior to computer imaging.

As well as providing to teachers tools with which to stimulate their students' scientific curiosity, such training can introduce teachers to the way that scientists approach their own investigations. By learning about the creativity of the scientific process, teachers can overcome what is sometimes an initial discomfort with unfamiliar open-ended investigations and can learn to switch from the role of "expert" to that of a guide for their students' own explorations.

Such efforts at improving science education are not restricted to practicing teachers. Some of the problems in science teaching, especially in elementary and middle school, are due to the fact that as education majors, teachers are generally taught methods for science teaching in a context that is divorced from the actual practice of science. To remedy this, schools of education at a number of universities, often with NSF support, are beginning to collaborate with scientists to develop teacher training courses that incorporate both science and mathematics. For example, at the University of Dayton, elementary school teachers-to-be must take three semesters of such integrative science classes. Fast Plants are obviously wonderful tools for educating preservice science teachers, but they are by no means the only such tools. In fact, at the University of Wisconsin, an Education Scholars Program pairs preservice teachers with research scientists in fields from entomology to geology; the students then work with master teachers in the community to derive an instructional unit from their research experiences.

Improving science education is obviously a long-term project that will require not only a willingness on the part of teachers and school administrators to adopt new approaches to teaching science but also a willingness and desire on the part of scientists to take a more active role in precollege science education. Although this involvement can take many forms, Fast Plants exemplify one of the most exciting, if also the most labor-intensive: the development of educational materials from one's own research work. Many different areas of research can yield an educational unit: for instance, Sofer and Tompkins (1994) point out that investigations into the behavioral genetics of Drosophila might be of great interest to high school students.

As more and more such innovative curricular units are developed and adopted, more and more children will be taught science in a way that truly conveys its excitement. Whether or not these students choose a career in science may be less important, however, than the prospect that they will take into their adult lives a sense of what scientific investigation is and how science is relevant to their own understanding of the world.

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