As they learn to walk, crawl, and fly, biologically inspired robots advance both robotics and scientists’ understanding of how animals move.

The robots developed at Case Western Reserve University in Cleveland may have unimaginative names—Robot One, Robot Two, and Robot Three—but they make up for it in looks. "All three so far are six legged," explains Roger Quinn, the mechanical engineer who built them, "but they get more and more like an insect."

To be specific, they get more and more like a cockroach. The legs of Robot One, for instance, emerge from directly beneath its balsa-wood body and are distributed in the simplest possible hexagon. Robot Two adopts a sprawl posture, with the legs, cockroachlike, on the outside of the body. The legs of
Robot Three are specialized to look and act like cockroach legs--small, mobile front legs for grooming and exploring the environment; medium-sized middle legs; and big, powerful rear legs for running and jumping.

This biological mimicry gives Robot Three the general gestalt of the urban dweller’s worst nightmare: a 14-kilogram, bread-box-sized creation that not only looks like a cockroach but promises to walk, run, and jump like a cockroach. The only feature that’s obviously not inspired by biology is the tether that supplies power to the pneumatic air compressors which serve as muscles. This tether means Robot Three cannot move about on its own. But Robot Four--which will also be modeled after a cockroach, says Quinn, "only more so"--will carry its power supply with it. It "will be able to run around the campus," no doubt to the delight of Case Western students and faculty.

The Case Western robots are among the vanguard of a new army of biologically inspired robots emerging from laboratories throughout the world. Indeed, a revolution seems to be going on in robotics, fueled by new insights and generous financial support from the Defense Department--in particular, from the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR), which together are pumping tens of millions of dollars into the field.

This largesse is promoting a union between engineers and biologists, and is spawning a new generation of swimming, flying, and crawling robotic offspring. Alan Rudolph, manager of DARPA’s 2-year-old controlled biological and biomimetic systems program, says his goal is to create robots that can go where humans either can’t go or where it’s not safe to send them, such as the surfaces of other planets, the bowels of a burning building, or the risky confines of a minefield or a battlefield. The idea, he says, is to take inspiration from the natural world, rather than build on existing machines. Why use two legs or four wheels to maneuver when a six-legged insect will do the job better? If you want a vehicle that moves sideways and diagonally as effortlessly as back and forth, why not find your inspiration in an eight-legged spider that can do just that? To put it simply, why not let evolution do your thinking for you?

For biologists, the lure is to create a moving, three-dimensional model to test their theories of how animals function. "The experiments you do on the robots tell you what you ought to be looking for within the animal," explains Joseph Ayers, a neurophysiologist at Northeastern University in Boston, who is now working on a robot lobster (see sidebar on p. 82). "To say it works both ways is an understatement."

Gil Pratt, for instance, an electrical engineer and computer scientist who runs the Leg Lab at the Massachusetts Institute of Technology (MIT), describes his motivation as twofold: to build a robot to do housework for him--"I’m a lazy person by nature," he explains--and to understand the mechanisms of control, balance, and locomotion in animals and insects. "It’s very easy to theorize about how biological systems work. What’s great about building robots is you can actually test the theories."

"The art in this is what you take from biology," adds Michael Dickinson, a neurobiologist at the University of California, Berkeley, who is working on a robot fly with DARPA support. "If you really want to make a useful robot, you don’t want to just copy nature. You want to extract principles at the right level"--even if the resulting robot doesn’t look much like the organism that inspired it (see sidebar on p. 81).

From animals to robots
Robot-building collaborations are often sprawling and involve unlikely partners: computer scientists, mathematicians, electrical and mechanical engineers, as well as biologists and zoologists. At Case Western, for instance, the program started with Randall Beer, a computer scientist who was frustrated by the slow progress in artificial intelligence and thought guidance might be found in the nervous systems of simple insects. Beer began collaborating with Case Western biologists Roy Ritzman and Hillel Chiel, and created a computer simulation of a walking insect. They then recruited Quinn, the engineer, to build hardware models to test the software simulation in the real world. Robots One, Two,
and Three were born.

As each robot has progressively captured more of the mechanical and control complexity found in the animal, says Quinn, the robots have become increasingly capable. Robot Two, for instance, can walk over rough terrain, whereas Robot One cannot. Robot Three can climb. And having a larger-than-life-sized cockroach to manipulate has taught the biologists a lot, adds Ritzman. For example, to get the robots moving fluidly, the researchers needed to incorporate input from strain gauges in the body into the computer that controls the robots, suggesting that the actual animal relies on organic structures that do the same thing, he says. "These insights have led us to propose many more experiments in the future" on the cockroaches themselves.

Beer eventually returned to the world of software simulations, while Ritzman--who spent 20 years studying the instinctive mechanism the cockroach uses to flee predators or an approaching rolled-up newspaper--has continued to work with Quinn on robots. "We started getting a lot of money from DARPA to build robots based on how cockroaches walk. I started getting less money for cockroach escape, so I took the hint," he says. "I thought I was getting into a hobby, and it took over my career."

Other biologists tell similar tales. Ayers, for example, spent much of his early career studying how the lobster’s nervous system controls its behavior and locomotion. Now he leads his own team of engineers working on a robot lobster, after he realized that the firing pattern the lobster’s nervous system uses to move the animal’s limbs would work well for almost any six-legged creature, including a robot one. He had his epiphany when DARPA asked him if it was possible to put sonar on live lobsters, apparently for use as unobtrusive underwater espionage agents. "I naïvely said it would be easier to build a lobster robot," says Ayers. "Now I appear to be a card-carrying roboticist, but it’s very clear to me that my training in neurophysiology is expert training for a roboticist and much better at the control end than anything a mechanical engineer gets."

For other researchers, robotics offered a new avenue of research when studies of live animals hit a dead end. Dickinson and Charlie Ellington of Cambridge University, for instance, both started off studying how real insects fly. Ellington’s lab gets credit for the observation that the flapping of insect wings seems to generate two to three times more lift than can be explained by conventional aerodynamics. (This led to the misconceived suggestion that science can’t explain why the bumblebee flies.) "We took our studies of real insects about as far as we could," says Ellington, "and we wanted them to do things that they couldn’t, so we had to build our own."

Specifically, Ellington concluded in the early 1990s that his research would benefit mightily from an insect that could release smoke from its wings on command, something real insects resolutely refused to do. So he and his colleagues built "the flapper," a mechanical, computer-controlled, scaled-up model of a Hawk moth that emits smoke as it flaps its mechanical wings, allowing Ellington and his colleagues to visualize the air flow around and over the wings. A similar line of thought led Dickinson and Berkeley engineer Ron Fearing to build a scaled-up model of a robotic fly. To create a robot big enough to work with, they had to scale up not just the fly’s body but the size and relative strength of the forces on it--the viscosity of air matters considerably more to a fly, for example, than it does to a pigeon. The researchers adjusted the forces to mimic those acting on a real fly by playing with variables such as the speed of the wings and the medium around them; they ended up with a robotic fly with a half-meter wingspan slowly flapping its wings in 2 tons of mineral oil. That robot allowed them to directly measure the forces generated by the wings.

In the last few years, Ellington’s and Dickinson’s labs together finally managed to explain the lift generated by insect wings. As published in a handful of papers, insect flight is the result of decidedly unconventional aerodynamics--a threesome of phenomena, involving the creation of a spiral leading-edge vortex (also known as a delayed stall), rotational lift, and wake capture. All three phenomena had been identified years ago and had been suspected of providing the necessary lift to insects, but the robots allowed researchers to measure the actual forces involved and provide the requisite experimental verification.
Now both groups are designing small flying robots for DARPA. Ellington says his recent wind-tunnel studies suggest that insect wings mounted on rotors, like a helicopter, generate as much lift as flapping insect wings and that a rotor design may be much more practical for a working robot. "My own aim," he says, "has always been to be able to build my own insect and fly it around the room under remote control. If you can do that, then you really understand how they’re flying." That goal, however, is still years away.

**Learning from robotuna**

A similar desire to understand how animals manage their feats of locomotion led Michael Triantafyllou, an MIT oceanographic engineer, to probe the secrets of fish propulsion. Triantafyllou decided to build a robot tuna to study underwater vortices, in particular the vortices that propel fish forward rather than dragging them back. Real tuna are champion long-distance swimmers, and so presumably their physiques are highly evolved to manipulate the forces around them as they swim. Triantafyllou and his collaborators used a taxidermist’s cast of a bluefin, then built an internal musculature of six "links," each of which can be swiveled back and forth by its own motor. The links are covered by plastic and aluminum ribs supporting a skin of padded foam and the same Lycra of which swimsuits are made. The 2-meter-long robotuna is only "a lab robot," says Triantafyllou, because it lives in its own water tank, the undersea version of a wind tunnel, and is attached to an overhead carriage through a thin strut that holds it in place and transmits commands and electricity to the motors. By using a robot tuna in lieu of the real thing, Triantafyllou and his colleagues can precisely control its motion and the amount of energy it expends to swim. They can then compare that energy to the propulsive force the robot exerts, while studying the flow of water over its body.

Triantafyllou and his colleagues realized that as the tuna swims, swishing its vertical tail fin from side to side, it minimizes the amount of energy needed to form the propulsion vortices while also controlling the flow around its body to reduce drag and turbulence. "Both mechanisms are hard at work," he says.

The MIT researchers then proceeded to build a robot pike. Their creation is about 1.3 meters long and composed of three links plus a tail. "This was primarily constructed to study acceleration," says Triantafyllou, as the pike is a "a very aggressive and agile fish, a master at fast starting and turning." The robopike is autonomous, meaning it needs no strut for support, has onboard batteries for power, and receives commands via a wireless modem in its nose. "You can put it in water and it starts swimming," says Triantafyllou.

By manipulating the robopike to precisely follow commands as real fish never would, Triantafyllou and colleagues learned how fish maneuver--"an exercise in vorticity control," says Triantafyllou. In order to turn, the fish has to push hard on the water to get going, and that requires, in effect, creating a temporary jet of water on one side. "The way they do it is by bending their body, which begins the formation of two very large vortices, and then the tail spins the one closest to the tail and then [the tail] spins the other vortex, closest to the head, to generate the two-vortex pair, which shoots out and generates the force needed for fast starting or turning."

Now, with support from ONR and DARPA, Triantafyllou and his colleagues are embarked on a pair of collaborations to build autonomous underwater vehicles (AUVs) that are more agile and maneuverable than existing miniature submarines. "If you compare a dolphin, for instance, with an AUV," says Triantafyllou, "the most striking difference is the ability of the dolphin to turn on a dime. So if you need to operate in areas that are cluttered, shallow, or with lots of waves, or if you want to do dangerous kinds of work, you want these very dexterous robots that can move quickly, position themselves in currents, and pack a lot of power."

The end result of all these collaborations is likely to be a world of new bio-inspired robots to help humans, although so far few robots have successfully made the leap out of the controlled environment of the lab into the unpredictable territory of the real world. Advocates argue that there’s another
reason for pursuing this line of work: The technology developed will likely yield tremendous unforeseen benefits later--what Dickinson calls "the moon shot" rationale. "The amount of technology that needs to be developed to build something like an autonomously flying insect is extraordinary," he says. "Fifty years from now, people will be talking about the technology that came off these projects in the same way they now talk about the technology that came out of the space program. There’s nowhere near the same amount of money going into it, but we’re going to reap similar rewards in terms of the technology."