A Cricket Robot

*Can a simple electromechanical system perform
a complex behavior of a living creature?
There was one sure way to find out*

by Barbara Webb

When we describe a behavior as robotic, it is usually to call attention to its predictability. Whether the subject is a bored supermarket cashier or an acquaintance not known for spontaneity, robotic behavior might be characterized as a series of seemingly automatic reactions in response to interactions or events.

Insect behavior, too, might be considered to be robotic or automatic. Detailed research into the specific actions of some insects, however, has revealed a great deal more variety than this characterization suggests. The female cricket attempting to locate a mate from the male's calling song is a good example. In some respects, this activity seems very simple: when she hears the appropriate song, the insect may continue to walk toward it for hours, even if placed on a treadmill.

Nevertheless, investigations over the past 20 years have uncovered many subtle details of this basic behavior. For instance, a female can distinguish the song of a male of her own species from any other noise and approach that one male even when other males of her own species are serenading her simultaneously with almost identical songs. We do not yet understand precisely how she accomplishes this and related feats.

Similarly, the behavior of robots can seem at once straightforward and complex. No matter how simple a robot may be, the interaction of its sensors and actuators with the environment is always complicated. This means that it is usually more difficult than it seems to get a consistent and reliable automatic response to a stimulus. For example, moving a wheeled robot in a straight line

is not just a matter of supplying motors on each side with the same power. Mechanical inaccuracies of motors, gears and wheels will require a slightly different power to get the same turn rate from the wheels. Friction and inertial forces will vary, and the power will have to be adjusted constantly from measurements of the turning rate and feedback of the error. Even when the wheels turn at the same rate, unevenness in the ground and slipperiness will move the robot off a true straight line unless it has some compass sense that allows it to change wheel speeds to compensate.

Counteracting the complex effects of the environment thus seems to require control algorithms of a matching sophistication. But does it really? An alternative, increasingly popular approach in robotics is to design the robot so that its interaction with the environment is exploited rather than resisted. For example, instead of attempting to force the robot to travel a straight-line course, it could be programmed to follow contours of the terrain that lead to its destination—circumventing rather than conquering hills in its path. Through this type of approach, what seems like complex behavior in a robot can come from a surprisingly uncomplicated control algorithm.

To investigate these issues, I designed and built a cricket robot based on relatively simple hardware, principles and algorithms. The behavior of this robot, I hoped, would have much of the complexity of the insect itself when confronted with a similar environment. I also hoped to cast some light on the neurobiology that may underlie cricket behavior.

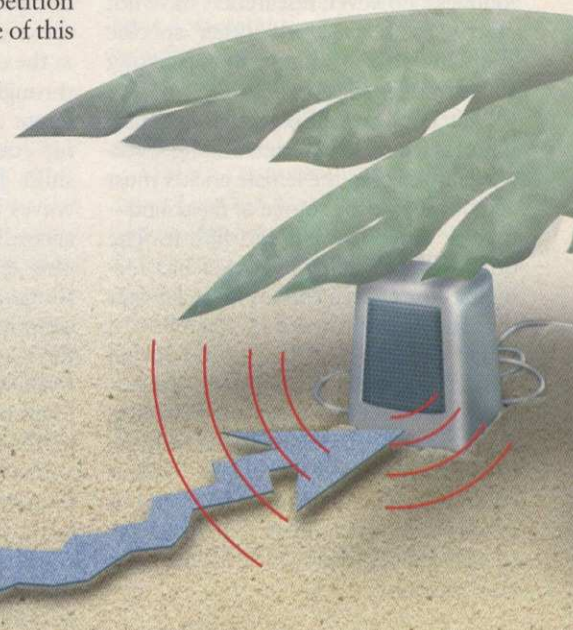Of course, it was not possible to model in minute detail all aspects of a crick-et's behavior, so I chose the specific but significant activity mentioned above: the ability of the female to identify and locate a singing male of her species. (This process of moving to a specific sound, along with all the sensory and locomotive requirements that it entails, is known as phonotaxis.)

Female crickets are quite selective with regard to the sounds that attract them. First, the song's underlying, or carrier, frequency is its most distinctive feature. Males can produce an almost pure tone by rubbing one wing against the other, and females of the same species respond best to that tone and not to sounds of lower or higher frequency than the carrier, which is generally around 4.5 kilohertz. Second, the rhythm of the song as the male opens and closes its wings is also distinctive and species-specific. Each rub of the wings creates the characteristic burst of sound known as a syllable; experiments have established that the rate with which syllables are repeated by the male insect—the syllable repetition rate—is the most essential feature of this

pattern for eliciting a female response.

Although in many species the noise is more extensively patterned—for example, syllables are repeated three to five times in a group known as a chirp, followed by a period of silence before the next chirp—many females will respond to syllables that are repeated over and over again, separated by an unvarying interval. Not only must the female cricket distinguish the correct rhythm and sound of a male of her species, but she must also often do so when a number of potential partners are simultaneously serenading her. Somehow she manages to direct herself toward only one of these suitors, ignoring the rest.

In the laboratory the main preference shown is for louder songs; presented with two songs that both have the correct syllable repetition rate, the female will move toward the louder of the two. A louder song may indicate a male who

CRICKET ROBOT mimicked one behavior of a female cricket: locating a male from the sound of his chirping. In the experiments, the robot moved in a small arena toward a speaker emitting a noise modeled on the sound produced by a male cricket. Like a real female cricket, the robot processed the sounds immediately on "hearing" them, enabling it to correct its course as it moved toward its destination. The path it took to the speaker zigzagged much like the route of a female cricket moving toward a mate; this path was never more than twice the direct distance from the starting point to the speaker.

is larger or simply closer. Other than loudness, however, researchers have not clearly established any other specific characteristics of naturally occurring songs that females prefer.

After choosing the correct sound and, if necessary, selecting from among several examples of it, the female cricket must actually locate the source of the sound—that is, move toward and find it. The only evidence that the cricket has recognized or chosen the sound is the fact that she moves toward it. Therefore, a single process—one that could locate only certain kinds of sound—might suffice to produce the observed behavior. If this were the case, the apparently selective behavior of the female cricket could be replicated by building a robot in which the mechanism that enables it to locate sound works only for the right kind of sound.

Through a Cricket's Ear

A cricket has a rather ingenious sensory mechanism that enables it to detect the direction of sound sources. Its ears are on its forelegs, and because the cricket's body is a poor shield for low-frequency sounds, there is little difference in the strength, or amplitude, of the sound received at each of its two ears. There is a difference in the times at which the sound arrives, but this difference is measured in microseconds and cannot be timed by the cricket's auditory neurons.

Sound passes along a tracheal tube that connects the ears to each other and to further openings, called spiracles, on the cricket's body. Hence, sound arrives at the ear both externally and internally through the tube, having traveled different distances. The time that it takes for sound to travel through the tube shifts its phase. At the eardrum, the waves reinforce or cancel one another according to their relative phase, which also depends on the direction of the sound. Therefore, the amplitude of the resulting eardrum vibration represents the direction of the sound source [see bottom illustration on opposite page]. Conveniently, the amplitude is larger on the side closer to the sound.
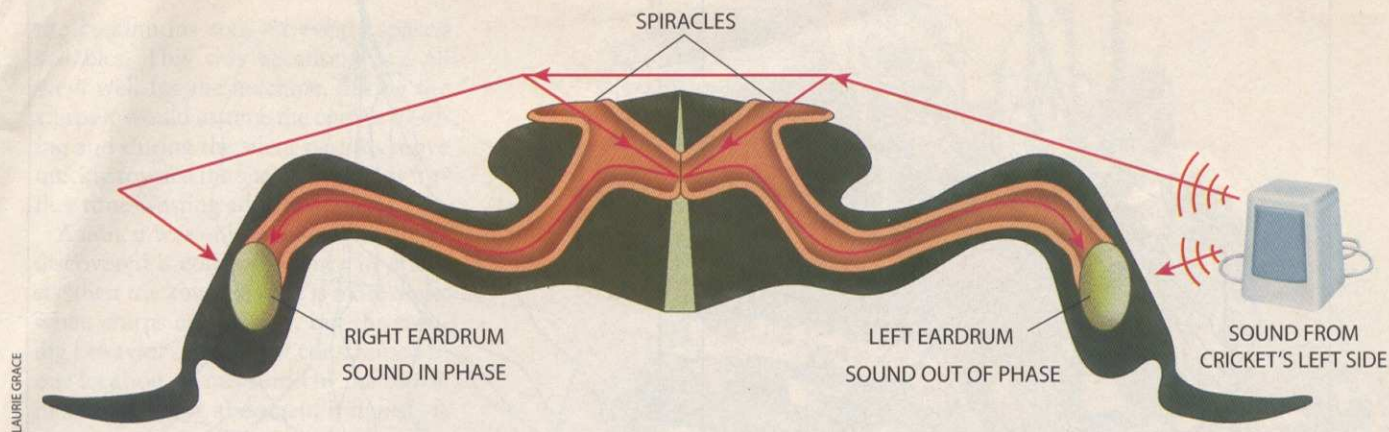
The "ears" of the robot I built were miniature microphones. With a great deal of help, I designed an electronic circuit that processed the signals in a way that mimicked the basic functions of a cricket's auditory system. One of the fundamental principles of this system is that the cricket's tracheal tube best transmits sounds of the desired calling song frequency, and the phase shifts in this transmission are suited to that particular wavelength. The mechanism does not reliably detect the direction of sounds at other frequencies. In other words, by relying on phase shifts tuned only to the right wavelength, the auditory system inherently ignores sounds of the wrong wavelength, because they do not produce a directional response.

The robot was a small vehicle, cubic in shape and about 20 centimeters on a side. Built with Lego bricks, the robot had two drive wheels and a caster on the front. As it was rather larger than a cricket, its ears were farther apart, and so I chose a lower frequency (two kilohertz) for the song that would attract it. The output from the microphone circuit provided a signal every 30 milliseconds. This signal corresponded to the eardrum vibration. Mimicking what occurs in a real cricket auditory system, the signal from the circuit had a higher amplitude on the side of the sound source, for sound of the right frequency. In practice, however, the robot's ears signaled the correct direction at best 90 percent of the time because of unwanted noise—in the speaker, in the room and from the robot's own motors.

The difference in vibration amplitude at the eardrums has to be neurally encoded if it is to be compared and used to drive the motor response. In the cricket, approximately 50 sensory neurons per ear converge on a small number of interneurons in the insect's central nervous system. Two of these interneurons—one connected to the left ear and the other to the right—form a pair that appears to be critical to phonotaxis. Neurophysiologists can measure and manipulate the firing of this neuron pair while the animal is walking in response to sound. By doing so, they have shown that the animal always turns to the side on which one member of this neuron pair is responding more strongly.

When a burst of sound occurs, each member of the neuron pair sums the input from the sensory neurons in the cor-

SPIRACLES

RIGHT EARDRUM
SOUND IN PHASE

LEFT EARDRUM
SOUND OUT OF PHASE

SOUND FROM
CRICKET'S LEFT SIDE

CRICKET'S BODY channels sounds through an internal tracheal tube that connects the insect's ears to each other and to two openings, called spiracles, at the top of the body (*above*). Each ear is near a knee on a front leg (*photograph, left*). Because of the tube, sound reaches each ear in two ways: directly from the sound source, and indirectly, via the tube, from the spiracles and other ear. At the ear closer to the sound source, the sound that has traveled directly to the outside of the eardrum has traveled a shorter distance than the sound arriving through the tube at the inside of the eardrum. Because of this difference in distance, the sound arriving at one side of this eardrum is out of phase with respect to the sound arriving at the other side. At this eardrum the out-of-phase waves are summed, causing a vibration of greater amplitude, sensed as a louder sound.

responding ear and, after a threshold is reached, starts firing. How quickly the firing starts depends on the strength of the input; how frequently the firing occurs also closely correlates with the strength of the input. Therefore, there are two ways that the eardrum vibration is encoded by the activity of neurons: the latency (the time that passes before the neurons start firing) and the rate of neural firing during the burst of sound. After a burst of sound ends, the neuron takes a short while to return to its resting state. If another sound begins during this recovery time, the firing recommences more rapidly because the neuron is already close to its threshold.

The most straightforward way the female cricket's nervous system might use this response to locate the sound is, at each sound burst, to turn to the side on which the firing begins first. (This way, she would be turning toward the side on which the sound is closer.) A significant consequence of this scenario is that a response occurs only at the beginning of a sound burst. This notion fits neatly with the fact that syllable repetition is the most important factor in determining whether a female responds to a song. If the sound is continuous or repeats more rapidly than the neuron's recovery time, the neuronal firing will be continuous. In this case, the side on which the neurons began firing first will be unclear. If, on the other hand, the sound repeats too slowly, the information about which way to turn will arrive less frequently and may not be enough to steer the fe-
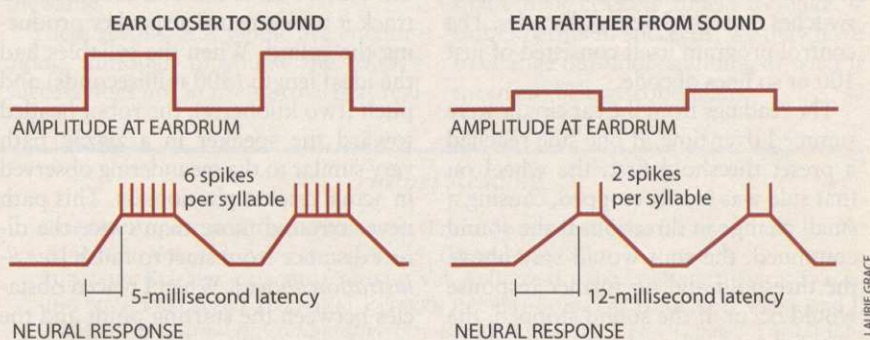
male toward the male. A particular repetition rate between these two extremes would of course be ideal.

Song of the Cricket Robot

The alternative to comparing onset times is comparing firing rates, which seems to cause the cricket to turn to the side that is firing more frequently. (This response also corresponds to an insect's turning toward the side on which the sound is closer.) This mechanism is the more popular hypothesis among neurophysiologists, although no definitive evidence exists for either possibility. Because firing rate will signal direction for any sound pattern—continuous

sound, fast or slow syllable repetition—this hypothesis requires that the cricket have some additional neural processes by which it picks out songs of the right rhythm. Indeed, certain neurons have been found in the cricket brain that appear to have this property.

These facts notwithstanding, for my robot I used an algorithm based on comparing the onset time and ignoring the firing rate. I wanted to test whether such a mechanism can explain the observed selectivity of the female for certain songs, without further neural processes. Because my robot's sensory system depended on having a particular wavelength of sound, and its "neural" comparator depended on having a particu-

EAR CLOSER TO SOUND

AMPLITUDE AT EARDRUM

6 spikes
per syllable

5-millisecond latency

NEURAL RESPONSE

EAR FARTHER FROM SOUND

AMPLITUDE AT EARDRUM

2 spikes
per syllable

12-millisecond latency

NEURAL RESPONSE

RESPONSE OF AUDITORY INTERNEURON depends on the direction of the sound source. The mechanical amplitude of the eardrum vibration (*top waveforms*) is greater at the eardrum closer to the sound source (*top left*). Each "square" in the waveform is in response to one sound, or syllable, from a male cricket. The interneuron that corresponds to the closer ear responds to the higher-amplitude vibration by rising in potential relatively quickly and by peaking, or "spiking," in potential six times (*lower left*). For the farther ear, the rise in potential is slower and the spikes fewer (*lower right*).
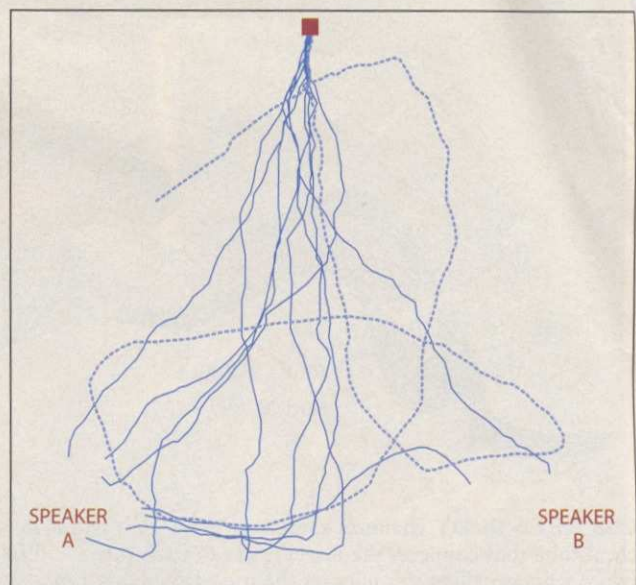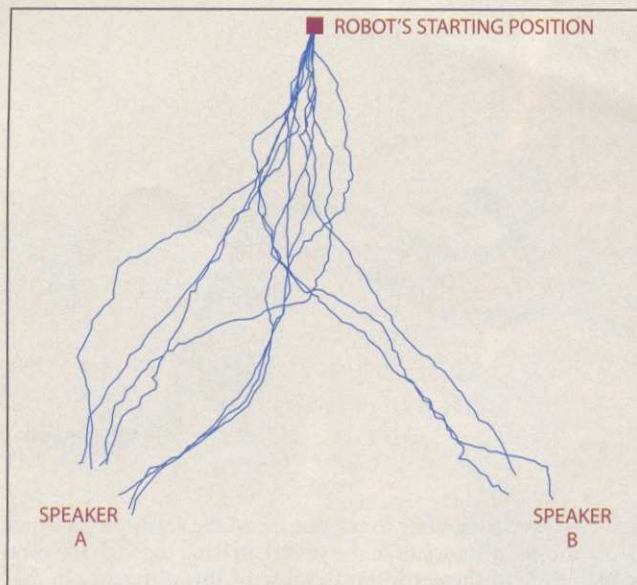
PATHS TO SOUND SOURCE taken by the robot were essentially indistinguishable from those taken by a cricket. The trials were all run in an arena four meters long by 3.3 meters wide. When sounds, known as syllables, were emitted by two speakers simultaneously, the robot simply traveled to one or the other (*left*). Female crickets also move toward a single chirping male when a number are chirping. When the syllables alternated between the two speakers, the robot's paths became more aimless, with the vehicle often winding up between the speakers (*right*). Again, females displayed similar behavior in this situation.

lar rhythm, it did not need to select the right song actively—it simply did not work for the wrong song. If my robot performed well in locating appropriate songs, this would lend credence to the hypothesis that the location mechanism of real crickets could also function in this way.

Programming the robot to function in this manner was relatively easy. Its "brain" was a 68000-type microprocessor, programmed to take various sensor inputs and to send start and stop commands to the right and left motors. In addition to the microphones and the circuit that modeled the phase delay and canceling in the cricket's auditory system, the robot had infrared and bump switches that could detect obstacles. The control program itself consisted of just 100 or so lines of code.

The readings from the ear circuit were summed over time. If one side reached a preset threshold first, the wheel on that side was briefly stopped, causing a small change in direction. If the sound continued, the sum would stay above the threshold and no further response would occur. If the sound stopped, the sum fell back toward zero, mimicking the recovery time of the cricket neuron. Thus, only discontinuous sound that repeated frequently would cause the robot to respond often enough to turn toward the sound.

Because the robot processed sound more slowly than a cricket, the syllable pattern of the song had to be slowed by a factor of about 10, to 300 milliseconds per syllable. Despite this slower sound pattern, the robot still turned and moved forward quite rapidly, with something like the speed of a real cricket. In other words, the robot changed direction at the speed of a cricket while receiving information at only one tenth the speed. Effectively, the robot had a more difficult task. The bright side was that I could be sure that if the robot was able to find the sound, it was certainly not beyond the capacity of the cricket to do so in the same way.

I put the robot through a series of trials. In each trial, I started the robot at one side of an arena and recorded the track it took toward a speaker producing the sound. When the syllables had the ideal length (300 milliseconds) and pitch (two kilohertz), the robot headed toward the speaker in a zigzag path very similar to the meandering observed in actual cricket phonotaxis. This path never covered more than twice the direct distance from start to finish [*see illustration above*]. When I placed obstacles between the starting point and the sound source, the robot found its way around them to the speaker.

To find out how the robot would react to sounds differing from the ideal, I carried out a series of trials with different syllable rates. When I increased the syllable rate (with syllables and gaps lasting less than 200 milliseconds), the robot's program could no longer distinguish the gaps in the sound. It would send very few turn signals to the motors, driving the robot in straight lines around the arena. If it found the speaker at all, it was mostly by chance. When I decreased the rate (syllables and gaps lasting more than 500 milliseconds), the behavior was also less successful. The turns became less frequent, and the robot ended up taking a curved path in the general direction of the speaker, which it often failed to reach. Although I expected that the robot would succeed only within a certain range of syllable rates, I discovered afterward that real crickets, too, tend to take curved paths at slower rates while failing more completely for faster rates. So the robot not only succeeds like a cricket but tends to fail like one, too.

The fact that a male cricket's song is actually a series of chirps—three or so syllables separated by periods of silence—has been more or less disregarded in the above discussion. During our trials, however, I thought it might be interesting to see how well the robot navigated when the syllable train was broken up into chirps. The results were mixed. The robot could move quite a long way in the arena during the silences between chirps, so it tended to overshoot the speaker and then take a while to recover its bearings. On the other hand, when it did reach the speaker, it got there more rapidly than it had with

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the continuous song of evenly spaced syllables. This was because when all went well for the machine, during the chirps it would assume the correct heading and during the silent periods move quickly toward the speaker without further time-wasting adjustments.

Again, it was only subsequently that I discovered a correspondence in crickets: their tracking behavior is more direct when chirps are present, but the turning behavior of a cricket constrained to one location, as measured by the movement of legs (or abdomen, if flying), is stronger with continuous syllables. The evidence from the robot suggests that situational factors, rather than additional neural processing mechanisms, may explain the effects of chirp structure on the female's movement toward a potential mate.

Surprising Similarities

So far the results had shown that the robot could mimic the cricket's recognition and location of the correct song. But could this simple vehicle, like a female cricket, choose one calling male from among several? I didn't think so, but it was easy to answer this question by adding a second speaker to the arena and playing the sound through both. To my surprise, the robot seemed to have no problem making up its mind (so to speak) and went almost directly to one speaker or the other.

Because I programmed the robot, I knew it was not capable of distinguishing or deciding between the sounds. Yet again it appears that it is the interaction of the robot's uncomplicated mechanisms with particular sound fields that produces this interesting—and useful—behavior. It might even be enough to explain how the female cricket selects a mate. Unfortunately, in these experiments I did not have enough control over the properties of the stimulus to test whether the robot would prefer certain songs over others.

One variation on two sound sources was possible, however: I could test the behavior when the song was split between the speakers, with syllables coming alternately from either side. Obviously, this situation does not occur in nature, and it is just as well. A female cricket presented with this scenario becomes confused and moves between the two sounds. The robot did more or less the same.

These results as a whole are encouraging, although of course the robot's success does not in itself prove that real crickets work this way. Nevertheless, it does suggest some alternative interpretations of neurophysiological and behavioral results. More generally, it shows that a rather competent and complex performance can come from a simple control mechanism, provided it interacts in the right way with its environment. My colleagues and I are now reimplementing this mechanism on a smaller robot that can process sound more rapidly; we should then be able to test it with recordings of real cricket songs to see if it makes the same choices that female crickets appear to make. If this experiment succeeds, we may have to change our understanding of what it means to behave robotically. SA

ROBERT P. CARR Bruce Coleman Inc. (animal); BARBARA WEBB (model)

ROBOTIC AND REAL CRICKETS differ in many physical attributes, including size. In the author's experiments, characteristics of the sounds and environment were scaled to the robot. In future experiments, however, cricket-size robots will be tested with the recorded songs of real male crickets.

The Author

BARBARA WEBB received a B.S. (and a University Medal) in psychology from the University of Sydney in 1987 and a Ph.D. in artificial intelligence from the University of Edinburgh in 1993. She is currently a lecturer in the department of psychology at the University of Nottingham, where she teaches artificial intelligence. Her main research interest is in perceptual systems for the control of behavior in robots and lower animals. Her other professional interests include cricket escape behavior and the modeling of the use by insects of polarized light in navigation.

Further Reading

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