The Intelligent Plant

Scientists debate a new way of understanding flora.

By Michael Pollan

Dec 15, 2013 11:00 PM · 37 min. read · View original

In 1973, a book claiming that plants were sentient beings that feel emotions, prefer classical music to rock and roll, and can respond to the unspoken thoughts of humans hundreds of miles away landed on the New York *Times* best-seller list for nonfiction. "The Secret Life of Plants," by Peter Tompkins and Christopher Bird, presented a beguiling mashup of legitimate plant science, quack experiments, and mystical nature worship that captured the public imagination at a time when New Age thinking was seeping into the mainstream. The most memorable passages described the experiments of a former C.I.A. polygraph expert named Cleve Backster, who, in 1966, on a whim, hooked up a galvanometer to the leaf of a dracaena, a houseplant that he kept in his office. To his astonishment, Backster found that simply by imagining the dracaena being set on fire he could make it rouse the needle of the polygraph machine, registering a surge of electrical activity suggesting that the plant felt stress. “Could the plant have been reading his mind?” the authors ask. “Backster felt like running into the street and shouting to the world, ‘Plants can think!’ ”

Backster and his collaborators went on to hook up polygraph machines to dozens of plants, including lettuces, onions, oranges, and bananas. He claimed that plants reacted to the thoughts (good or ill) of humans in close proximity and, in the case of humans familiar to them, over a great distance. In one experiment designed to test plant memory, Backster found that a plant that had witnessed the murder (by stomping) of another plant could pick out the killer from a lineup of six suspects, registering a surge of electrical activity when the murderer was brought before it. Backster’s plants also displayed a strong aversion to interspecies violence. Some had a stressful response when an egg was cracked in their presence, or when live shrimp were dropped into boiling water, an experiment that Backster wrote up for the *International Journal of Parapsychology*, in 1968.

In the ensuing years, several legitimate plant scientists tried to reproduce the “Backster effect” without success. Much of the science in “The Secret Life of Plants” has been discredited. But the book had made its mark on the culture. Americans began talking to their plants and playing Mozart for them, and no doubt many still do. This might seem harmless enough; there will probably always be a strain of romanticism running through our thinking about plants. (Luther Burbank and George Washington Carver both reputedly talked to, and listened to, the plants they did such brilliant work with.) But in the view of many plant scientists "The Secret Life of Plants" has done lasting damage to their field. According to Daniel Chamovitz, an Israeli biologist who is the author of the recent book "What a Plant Knows," Tompkins and Bird "stymied important research on plant behavior as scientists became wary of any studies that hinted at parallels between animal senses and plant senses." Others contend that "The Secret Life of Plants" led to "self-censorship" among researchers seeking to explore the "possible homologies between neurobiology and phytobiology"; that is, the possibility that plants are much more intelligent and much more like us than most people think—capable of cognition, communication, information processing, computation, learning, and memory.

The quotation about self-censorship appeared in a controversial 2006 article in *Trends in Plant Science* proposing a new field of inquiry that the authors, perhaps somewhat recklessly, elected to call "plant neurobiology." The six authors—among them Eric D. Brenner, an American plant molecular biologist; Stefano

Mancuso, an Italian plant physiologist; František Baluška, a Slovak cell biologist; and Elizabeth Van Volkenburgh, an American plant biologist—argued that the sophisticated behaviors observed in plants cannot at present be completely explained by familiar genetic and biochemical mechanisms. Plants are able to sense and optimally respond to so many environmental variables—light, water, gravity, temperature, soil structure, nutrients, toxins, microbes, herbivores, chemical signals from other plants—that there may exist some brainlike information-processing system to integrate the data and coördinate a plant's behavioral response. The authors pointed out that electrical and chemical signalling systems have been identified in plants which are homologous to those found in the nervous systems of animals. They also noted that neurotransmitters such as serotonin, dopamine, and glutamate have been found in plants, though their role remains unclear.

Hence the need for plant neurobiology, a new field "aimed at understanding how plants perceive their circumstances and respond to environmental input in an integrated fashion." The article argued that plants exhibit intelligence, defined by the authors as "an intrinsic ability to process information from both abiotic and biotic stimuli that allows optimal decisions about future activities in a given environment." Shortly before the article's publication, the Society for Plant Neurobiology held its first meeting, in Florence, in 2005. A new scientific journal, with the less tendentious title *Plant Signaling & Behavior,* appeared the following year.

Depending on whom you talk to in the plant sciences today, the field of plant neurobiology represents either a radical new paradigm in our understanding of life or a slide back down into the murky scientific waters last stirred up by "The Secret Life of Plants." Its proponents believe that we must stop regarding plants as passive objects—the mute, immobile furniture of our world—and begin to treat them as protagonists in their own dramas, highly skilled in the ways of contending in nature. They would challenge contemporary biology's reductive focus on cells and genes and return our attention to the organism and its behavior in the environment. It is only human arrogance, and the fact that the lives of plants unfold in what amounts to a much slower dimension of time, that keep us from appreciating their intelligence and consequent success. Plants dominate every terrestrial environment, composing ninety-nine per cent of the biomass on earth. By comparison, humans and all the other animals are, in the words of one plant neurobiologist, "just traces."

Many plant scientists have pushed back hard against the nascent field, beginning with a tart, dismissive letter in response to the Brenner manifesto, signed by thirty-six prominent plant scientists (Alpi et al., in the literature) and published in *Trends in Plant Science*. "We begin by stating simply that there is no evidence for structures such as neurons, synapses or a brain in plants," the authors wrote. No such claim had actually been made—the manifesto had spoken only of "homologous" structures—but the use of the word "neurobiology" in the absence of actual neurons was apparently more than many scientists could bear.

"Yes, plants have both short- and long-term electrical signalling, and they use some neurotransmitter-like chemicals as chemical signals," Lincoln Taiz, an emeritus professor of plant physiology at U.C. Santa Cruz and one of the signers of the Alpi letter, told me. "But the mechanisms are quite different from those of true nervous systems." Taiz says that the writings of the plant neurobiologists suffer from "over-interpretation of data, teleology, anthropomorphizing, philosophizing, and wild speculations." He is confident that eventually the plant behaviors we can't yet account for will be explained by the action of chemical or electrical pathways, without recourse to "animism." Clifford Slayman, a professor of cellular and molecular physiology at Yale, who also signed the Alpi letter (and who helped discredit Tompkins and Bird), was even more blunt. " 'Plant intelligence' is a foolish distraction, not a new paradigm," he wrote in a recent e-mail. Slayman has referred to the Alpi letter as "the last serious confrontation between the scientific community and the nuthouse on these issues." Scientists seldom use such language when talking about their colleagues to a journalist, but this issue generates strong feelings, perhaps because it smudges the sharp line separating the animal kingdom from the plant kingdom. The controversy is less about the remarkable discoveries of recent plant science than about how to interpret and name them: whether behaviors observed in plants which look very much like learning, memory, decision-making, and intelligence deserve to be called by those terms or whether those words should be reserved exclusively for creatures with brains.

No one I spoke to in the loose, interdisciplinary group of scientists working on plant intelligence claims that plants have telekinetic powers or feel emotions. Nor does anyone believe that we will locate a walnut-shaped organ somewhere in plants which processes sensory data and directs plant behavior. More likely, in the scientists' view, intelligence in plants resembles that exhibited in insect colonies, where it is thought to be an emergent property of a great many mindless individuals organized in a network. Much of the research on plant intelligence has been inspired by the new science of networks, distributed computing, and swarm behavior, which has demonstrated some of the ways in which remarkably brainy behavior can emerge in the absence of actual brains.

"If you are a plant, having a brain is not an advantage," Stefano Mancuso points out. Mancuso is perhaps the field's most impassioned spokesman for the plant point of view. A slight, bearded Calabrian in his late forties, he comes across more like a humanities professor than like a scientist. When I visited him earlier this year at the International Laboratory of Plant Neurobiology, at the University of Florence, he told me that his conviction that humans grossly underestimate plants has its origins in a science-fiction story he remembers reading as a teen-ager. A race of aliens living in a radically sped-up dimension of time arrive on Earth and, unable to detect any movement in humans, come to the logical conclusion that we are "inert material" with which they may do as they please. The aliens proceed ruthlessly to exploit us. (Mancuso subsequently wrote to say that the story he recounted was actually a mangled recollection of an early "Star Trek" episode called "Wink of an Eye.")

In Mancuso's view, our "fetishization" of neurons, as well as our tendency to equate behavior with mobility, keeps us from appreciating what plants can do. For instance, since plants can't run away and frequently get eaten, it serves them well not to have any irreplaceable organs. “A plant has a modular design, so it can lose up to ninety per cent of its body without being killed,” he said. “There’s nothing like that in the animal world. It creates a resilience.”

Indeed, many of the most impressive capabilities of plants can be traced to their unique existential predicament as beings rooted to the ground and therefore unable to pick up and move when they need something or when conditions turn unfavorable. The “sessile life style,” as plant biologists term it, calls for an extensive and nuanced understanding of one’s immediate environment, since the plant has to find everything it needs, and has to defend itself, while remaining fixed in place. A highly developed sensory apparatus is required to locate food and identify threats. Plants have evolved between fifteen and twenty distinct senses, including analogues of our five: smell and taste (they sense and respond to chemicals in the air or on their bodies); sight (they react differently to various wavelengths of light as well as to shadow); touch (a vine or a root “knows” when it encounters a solid object); and, it has been discovered, sound. In a recent experiment, Heidi Appel, a chemical ecologist at the University of Missouri, found that, when she played a recording of a caterpillar chomping a leaf for a plant that hadn’t been touched, the sound primed the plant’s genetic machinery to produce defense chemicals. Another experiment, done in Mancuso's lab and not yet published, found that plant roots would seek out a buried pipe through which water was flowing even if the exterior of the pipe was dry, which suggested that plants somehow "hear" the sound of flowing water.

The sensory capabilities of plant roots fascinated Charles Darwin, who in his later years became increasingly passionate about plants; he and his son Francis performed scores of ingenious experiments on plants. Many involved the root, or radicle, of young plants, which the Darwins demonstrated could sense light, moisture, gravity, pressure, and several other environmental qualities, and then determine the optimal trajectory for the root's growth. The last sentence of Darwin's 1880 book, "The Power of Movement in Plants," has assumed scriptural authority for some plant neurobiologists: "It is hardly an exaggeration to say that the tip of the radicle . . . having the power of directing the movements of the adjoining parts, acts like the brain of one of the lower animals; the brain being seated within the anterior end of the body, receiving impressions from the sense organs and directing the several movements." Darwin was asking us to think of the plant as a kind of upside-down animal, with its main sensory organs and "brain" on the bottom, underground, and its sexual organs on top.

Scientists have since found that the tips of plant roots, in addition to sensing gravity, moisture, light, pressure, and hardness, can also sense volume, nitrogen, phosphorus, salt, various toxins, microbes, and chemical signals from neighboring plants. Roots about to encounter an impenetrable obstacle or a toxic substance change course before they make contact with it. Roots can tell whether nearby roots are self or other and, if other, kin or stranger. Normally, plants compete for root space with strangers, but, when researchers put four closely related Great Lakes sea-rocket plants (*Cakile edentula*) in the same pot, the plants restrained their usual competitive behaviors and shared resources.

Somehow, a plant gathers and integrates all this information about its environment, and then "decides"—some scientists deploy the quotation marks, indicating metaphor at work; others drop them—in precisely what direction to deploy its roots or its leaves. Once the definition of "behavior" expands to include such things as a shift in the trajectory of a root, a reallocation of resources, or the emission of a powerful chemical, plants begin to look like much more active agents, responding to environmental cues in ways more subtle or adaptive than the word "instinct" would suggest. "Plants perceive competitors and grow away from them," Rick Karban, a plant ecologist at U.C. Davis, explained, when I asked him for an example of plant decision-making. “They are more leery of actual vegetation than they are of inanimate objects, and they respond to potential competitors before actually being shaded by them.” These are sophisticated behaviors, but, like most plant behaviors, to an animal they’re either invisible or really, really slow.

The sessile life style also helps account for plants’ extraordinary gift for biochemistry, which far exceeds that of animals and, arguably, of human chemists. (Many drugs, from aspirin to opiates, derive from compounds designed by plants.) Unable to run away, plants deploy a complex molecular vocabulary to signal distress, deter or poison enemies, and recruit animals to perform various services for them. A recent study in *Science* found that the caffeine produced by many plants may function not only as a defense chemical, as had previously been thought, but in some cases as a psychoactive drug in their nectar. The caffeine encourages bees to remember a particular plant and return to it, making them more faithful and effective pollinators.

One of the most productive areas of plant research in recent years has been plant signalling. Since the early nineteen-eighties, it has been known that when a plant’s leaves are infected or chewed by insects they emit volatile chemicals that signal other leaves to mount a defense. Sometimes this warning signal contains information about the identity of the insect, gleaned from the taste of its saliva. Depending on the plant and the attacker, the defense might involve altering the leaf's flavor or texture, or producing toxins or other compounds that render the plant's flesh less digestible to herbivores. When antelopes browse acacia trees, the leaves produce tannins that make them unappetizing and difficult to digest. When food is scarce and acacias are overbrowsed, it has been reported, the trees produce sufficient amounts of toxin to kill the animals.

Perhaps the cleverest instance of plant signalling involves two insect species, the first in the role of pest and the second as its exterminator. Several species, including corn and lima beans, emit a chemical distress call when attacked by caterpillars. Parasitic wasps some distance away lock in on that scent, follow it to the afflicted plant, and proceed to slowly destroy the caterpillars. Scientists call these insects "plant bodyguards."

Plants speak in a chemical vocabulary we can't directly perceive or comprehend. The first important discoveries in plant communication were made in the lab in the nineteen-eighties, by isolating plants and their chemical emissions in Plexiglas chambers, but Rick Karban, the U.C. Davis ecologist, and others have set themselves the messier task of studying how plants exchange chemical signals outdoors, in a natural setting. Recently, I visited Karban's study plot at the University of California's Sagehen Creek Field Station, a few miles outside Truckee. On a sun-flooded hillside high in the Sierras, he introduced me to the ninety-nine sagebrush plants—low, slow-growing gray-green shrubs marked with plastic flags—that he and his colleagues have kept under close surveillance for more than a decade.

Karban, a fifty-nine-year-old former New Yorker, is slender, with a thatch of white curls barely contained by a floppy hat. He has shown that when sagebrush leaves are clipped in the spring—simulating an insect attack that triggers the release of volatile chemicals—both the clipped plant and its unclipped neighbors suffer significantly less insect damage over the season. Karban believes that the plant is alerting all its leaves to the presence of a pest, but its neighbors pick up the signal, too, and gird themselves against attack. "We think the sagebrush are basically eavesdropping on one another," Karban said. He found that the more closely related the plants the more likely they are to respond to the chemical signal, suggesting that plants may display a form of kin recognition. Helping out your relatives is a good way to improve the odds that your genes will survive.

The field work and data collection that go into making these discoveries are painstaking in the extreme. At the bottom of a meadow raked by the slanted light of late summer, two collaborators from Japan, Kaori Shiojiri and Satomi Ishizaki, worked in the shade of a small pine, squatting over branches of sagebrush that Karban had tagged and cut. Using clickers, they counted every trident-shaped leaf on every branch, and then counted and recorded every instance of leaf damage, one column for insect bites, another for disease. At the top of the meadow, another collaborator, James Blande, a chemical ecologist from England, tied plastic bags around sagebrush stems and inflated the bags with filtered air. After waiting twenty minutes for the leaves to emit their volatiles, he pumped the air through a metal cylinder containing an absorbent material that collected the chemical emissions. At the lab, a gas chromatograph-mass spectrometer would yield a list of the compounds collected—more than a hundred in all. Blande offered to let me put my nose in one of the bags; the air was powerfully aromatic, with a scent closer to aftershave than to perfume. Gazing across the meadow of sagebrush, I found it difficult to imagine the invisible chemical chatter, including the calls of distress, going on all around—or that these motionless plants were engaged in any kind of "behavior" at all.

Research on plant communication may someday benefit farmers and their crops. Plant-distress chemicals could be used to prime plant defenses, reducing the need for pesticides. Jack Schultz, a chemical ecologist at the University of Missouri, who did some of the pioneering work on plant signalling in the early nineteen-eighties, is helping to develop a mechanical "nose" that, attached to a tractor and driven through a field, could help farmers identify plants under insect attack, allowing them to spray pesticides only when and where they are needed.

"This is where we practice our warning shots."

Karban told me that, in the nineteen-eighties, people working on plant communication faced some of the same outrage that scientists working on plant intelligence (a term he cautiously accepts) do today. “This stuff has been enormously contentious,” he says, referring to the early days of research into plant communication, work that is now generally accepted. “It took me years to get some of these papers published. People would literally be screaming at one another at scientific meetings.” He added, “Plant scientists in general are incredibly conservative. We all think we want to hear novel ideas, but we don’t, not really.”

I first met Karban at a scientific meeting in Vancouver last July, when he presented a paper titled “Plant Communication and Kin Recognition in Sagebrush.” The meeting would have been the sixth gathering of the Society for Plant Neurobiology, if not for the fact that, under pressure from certain quarters of the scientific establishment, the group’s name had been changed four years earlier to the less provocative Society for Plant Signaling and Behavior. The plant biologist Elizabeth Van Volkenburgh, of the University of Washington, who was one of the founders of the society, told me that the name had been changed after a lively internal debate; she felt that jettisoning “neurobiology” was probably for the best. “I was told by someone at the National Science

Foundation that the N.S.F. would never fund anything with the words 'plant neurobiology' in it. He said, and I quote, ' "Neuro" belongs to animals.' " (An N.S.F. spokesperson said that, while the society is not eligible for funding by the foundation's neurobiology program, "the N.S.F. does not have a boycott of any sort against the society.") Two of the society's co-founders, Stefano Mancuso and František Baluška, argued strenuously against the name change, and continue to use the term "plant neurobiology" in their own work and in the names of their labs.

The meeting consisted of three days of PowerPoint presentations delivered in a large, modern lecture hall at the University of British Columbia before a hundred or so scientists. Most of the papers were highly technical presentations on plant signalling—the kind of incremental science that takes place comfortably within the confines of an established scientific paradigm, which plant signalling has become. But a handful of speakers presented work very much within the new paradigm of plant intelligence, and they elicited strong reactions.

The most controversial presentation was "Animal-Like Learning in Mimosa Pudica," an unpublished paper by Monica Gagliano, a thirty-seven-year-old animal ecologist at the University of Western Australia who was working in Mancuso's lab in Florence. Gagliano, who is tall, with long brown hair parted in the middle, based her experiment on a set of protocols commonly used to test learning in animals. She focussed on an elementary type of learning called "habituation," in which an experimental subject is taught to ignore an irrelevant stimulus. "Habituation enables an organism to focus on the important information, while filtering out the rubbish," Gagliano explained to the audience of plant scientists. How long does it take the animal to recognize that a stimulus is "rubbish," and then how long will it remember what it has learned? Gagliano's experimental question was bracing: Could the same thing be done with a plant?

Mimosa pudica, also called the "sensitive plant," is that rare plant species with a behavior so speedy and visible that animals can observe it; the Venus flytrap is another. When the fernlike leaves of the mimosa are touched, they instantly fold up, presumably to frighten insects. The mimosa also collapses its leaves when the plant is dropped or jostled. Gagliano potted fifty-six mimosa plants and rigged a system to drop them from a height of fifteen centimetres every five seconds. Each "training session" involved sixty drops. She reported that some of the mimosas started to reopen their leaves after just four, five, or six drops, as if they had concluded that the stimulus could be safely ignored. "By the end, they were completely open," Gagliano said to the audience. "They couldn't care less anymore."

Was it just fatigue? Apparently not: when the plants were shaken, they again closed up. " 'Oh, this is something new,' " Gagliano said, imagining these events from the plants' point of view. "You see, you want to be attuned to something new coming in. Then we went back to the drops, and they didn't respond." Gagliano reported that she retested her plants after a week and found that they continued to disregard the drop stimulus, indicating that they "remembered" what they had learned. Even after twenty-eight days, the lesson had not been forgotten. She reminded her colleagues that, in similar experiments with bees, the insects forgot what they had learned after just forty-eight hours. Gagliano concluded by suggesting that "brains and neurons are a sophisticated solution but not a necessary requirement for learning," and that there is "some unifying mechanism across living systems that can process information and learn."

A lively exchange followed. Someone objected that dropping a plant was not a relevant trigger, since that doesn't happen in nature. Gagliano pointed out that electric shock, an equally artificial trigger, is often used in animal-learning experiments. Another scientist suggested that perhaps her plants were not habituated, just tuckered out. She argued that twenty-eight days would be plenty of time to rebuild their energy reserves.

On my way out of the lecture hall, I bumped into Fred Sack, a prominent botanist at the University of British Columbia. I asked him what he thought of Gagliano's presentation. "Bullshit," he replied. He explained that the word "learning" implied a brain and should be reserved for animals: "Animals can exhibit learning, but plants evolve adaptations." He was making a distinction between behavioral changes that occur within the lifetime of an organism and those which arise across generations. At lunch, I sat with a Russian scientist, who was equally dismissive. "It's not learning," he said. "So there's nothing to discuss."

Later that afternoon, Gagliano seemed both stung by some of the reactions to her presentation and defiant. Adaptation is far too slow a process to explain the behavior she had observed, she told me. "How can they be adapted to something they have never experienced in their real world?" She noted that some of her plants learned faster than others, evidence that "this is not an innate or programmed response." Many of the scientists in her audience were just getting used to the ideas of plant "behavior" and "memory" (terms that even Fred Sack said he was willing to accept); using words like "learning" and "intelligence" in plants struck them, in Sack's words, as "inappropriate" and "just weird." When I described the experiment to Lincoln Taiz, he suggested the words "habituation" or "desensitization" would be more appropriate than "learning." Gagliano said that her mimosa paper had been rejected by ten journals: "None of the reviewers had problems with the data." Instead, they balked at the language she used to describe the data. But she didn't want to change it. "Unless we use the same language to describe the same behavior"—exhibited by plants and animals—"we can't compare it," she said.

Rick Karban consoled Gagliano after her talk. "I went through the same thing, just getting totally hammered," he told her. "But you're doing good work. The system is just not ready." When I asked him what he thought of Gagliano's paper, he said, "I don't know if she's got everything nailed down, but it's a very cool idea that deserves to get out there and be discussed. I hope she doesn't get discouraged."

Scientists are often uncomfortable talking about the role of metaphor and imagination in their work, yet scientific progress often depends on both. "Metaphors help stimulate the investigative imagination of good scientists," the British plant scientist Anthony Trewavas wrote in a spirited response to the Alpi letter denouncing plant neurobiology. "Plant neurobiology" is obviously a metaphor—plants don't possess the type of excitable, communicative cells we call neurons. Yet the introduction of the term has raised a series of questions and inspired a set of experiments that promise to deepen our understanding not only of plants but potentially also of brains. If there are other ways of processing information, other kinds of cells and cell networks that can somehow give rise to intelligent behavior, then we may be more inclined to ask, with Mancuso, "What's so special about neurons?"

Mancuso is the poet-philosopher of the movement, determined to win for plants the recognition they deserve and, perhaps, bring humans down a peg in the process. His somewhat grandly named International Laboratory of Plant Neurobiology, a few miles outside Florence, occupies a modest suite of labs and offices in a low-slung modern building. Here a handful of collaborators and graduate students work on the experiments Mancuso devises to test the intelligence of plants. Giving a tour of the labs, he showed me maize plants, grown under lights, that were being taught to ignore shadows; a poplar sapling hooked up to a galvanometer to measure its response to air pollution; and a chamber in which a *PTR-TOF* machine—an advanced kind of mass spectrometer—continuously read all the volatiles emitted by a succession of plants, from poplars and tobacco plants to peppers and olive trees. “We are making a dictionary of each species’ entire chemical vocabulary,” he explained. He estimates that a plant has three thousand chemicals in its vocabulary, while, he said with a smile, “the average student has only seven hundred words.”

Mancuso is fiercely devoted to plants—a scientist needs to “love” his subject in order to do it justice, he says. He is also gentle and unassuming, even when what he is saying is outrageous. In the corner of his office sits a forlorn *Ficus benjamina,* or weeping fig, and on the walls are photographs of Mancuso in an astronaut’s jumpsuit floating in the cabin of a zero-gravity aircraft; he has collaborated with the European Space Agency, which has supported his research on plant behavior in micro- and hyper-gravity. (One of his experiments was carried on board the last flight of the space shuttle Endeavor, in May of 2011.) A decade ago, Mancuso persuaded a Florentine bank foundation to underwrite much of his research and help launch the Society for Plant Neurobiology; his lab also receives grants from the European Union.

Early in our conversation, I asked Mancuso for his definition of “intelligence.” Spending so much time with the plant neurobiologists, I could feel my grasp on the word getting less sure. It turns out that I am not alone: philosophers and psychologists have been arguing over the definition of intelligence for at least a century, and whatever consensus there may once have been has been rapidly slipping away. Most definitions of intelligence fall into one of two categories. The first is worded so that intelligence requires a brain; the definition refers to intrinsic mental qualities such as reason, judgment, and abstract thought. The second category, less brain-bound and metaphysical, stresses behavior, defining intelligence as the ability to respond in optimal ways to the challenges presented by one's environment and circumstances. Not surprisingly, the plant neurobiologists jump into this second camp.

"I define it very simply," Mancuso said. "Intelligence is the ability to solve problems." In place of a brain, "what I am looking for is a distributed sort of intelligence, as we see in the swarming of birds." In a flock, each bird has only to follow a few simple rules, such as maintaining a prescribed distance from its neighbor, yet the collective effect of a great many birds executing a simple algorithm is a complex and supremely well-coördinated behavior. Mancuso's hypothesis is that something similar is at work in plants, with their thousands of root tips playing the role of the individual birds—gathering and assessing data from the environment and responding in local but coördinated ways that benefit the entire organism.

“Neurons perhaps are overrated,” Mancuso said. “They’re really just excitable cells.” Plants have their own excitable cells, many of them in a region just behind the root tip. Here Mancuso and his frequent collaborator, František Baluška, have detected unusually high levels of electrical activity and oxygen consumption. They’ve hypothesized in a series of papers that this so-called “transition zone” may be the locus of the “root brain” first proposed by Darwin. The idea remains unproved and controversial. “What’s going on there is not well understood,” Lincoln Taiz told me, “but there is no evidence it is a command center.”

How plants do what they do without a brain—what Anthony Trewavas has called their “mindless mastery”—raises questions about how our brains do what they do. When I asked Mancuso about the function and location of memory in plants, he speculated about the possible role of calcium channels and other mechanisms, but then he reminded me that mystery still surrounds where and how our memories are stored: “It could be the same kind of machinery, and figuring it out in plants may help us figure it out in humans.”

“There’s so much evidence, we should put some aside for a different case.”

The hypothesis that intelligent behavior in plants may be an emergent property of cells exchanging signals in a network might sound far-fetched, yet the way that intelligence emerges from a network of neurons may not be very different. Most neuroscientists would agree that, while brains considered as a whole function as centralized command centers for most animals, within the brain there doesn’t appear to be any command post; rather, one finds a leaderless network. That sense we get when we think about what might govern a plant—that there is no there there, no wizard behind the curtain pulling the levers—may apply equally well to our brains.

In Martin Amis’s 1995 novel, “The Information,” we meet a character who aspires to write “The History of Increasing Humiliation,” a treatise chronicling the gradual dethronement of humankind from its position at the center of the universe, beginning with Copernicus. “Every century we get smaller,” Amis writes. Next came Darwin, who brought the humbling news that we are the product of the same natural laws that created animals. In the last century, the formerly sharp lines separating humans from animals—our monopolies on language, reason, toolmaking, culture, even self-consciousness—have been blurred, one after another, as science has granted these capabilities to other animals.

Mancuso and his colleagues are writing the next chapter in “The History of Increasing Humiliation.” Their project entails breaking down the walls between the kingdoms of plants and animals, and it is proceeding not only experiment by experiment but also word by word. Start with that slippery word “intelligence.” Particularly when there is no dominant definition (and when measurements of intelligence, such as I.Q., have been shown to be culturally biased), it is possible to define intelligence in a way that either reinforces the boundary between animals and plants (say, one that entails abstract thought) or undermines it. Plant neurobiologists have chosen to define intelligence democratically, as an ability to solve problems or, more precisely, to respond adaptively to circumstances, including ones unforeseen in the genome.

"I agree that humans are special," Mancuso says. "We are the first species able to argue about what intelligence is. But it's the quantity, not the quality" of intelligence that sets us apart. We exist on a continuum with the acacia, the radish, and the bacterium. "Intelligence is a property of life," he says. I asked him why he thinks people have an easier time granting intelligence to computers than to plants. (Fred Sack told me that he can abide the term "artificial intelligence," because the intelligence in this case is modified by the word "artificial," but not "plant intelligence." He offered no argument, except to say, "I'm in the majority in saying it's a little weird.") Mancuso thinks we're willing to accept artificial intelligence because computers are our creations, and so reflect our own intelligence back at us. They are also our dependents, unlike plants: "If we were to vanish tomorrow, the plants would be fine, but if the plants vanished . . ." Our dependence on plants breeds a contempt for them, Mancuso believes. In his somewhat topsy-turvy view, plants "remind us of our weakness."

"Memory" may be an even thornier word to apply across kingdoms, perhaps because we know so little about how it works. We tend to think of memories as immaterial, but in animal brains some forms of memory involve the laying down of new connections in a network of neurons. Yet there are ways to store information biologically that don't require neurons. Immune cells "remember" their experience of pathogens, and call on that memory in subsequent encounters. In plants, it has long been known that experiences such as stress can alter the molecular wrapping around the chromosomes; this, in turn, determines which genes will be silenced and which expressed. This so-called "epigenetic" effect can persist and sometimes be passed down to offspring. More recently, scientists have found that life events such as trauma or starvation produce epigenetic changes in animal brains (coding for high levels of cortisol, for example) that are long-lasting and can also be passed down to offspring, a form of memory much like that observed in plants.

While talking with Mancuso, I kept thinking about words like "will," "choice," and "intention," which he seemed to attribute to plants rather casually, almost as if they were acting consciously. At one point, he told me about the dodder vine, *Cuscuta europaea*, a parasitic white vine that winds itself around the stalk of another plant and sucks nourishment from it. A dodder vine will "choose" among several potential hosts, assessing, by scent, which offers the best potential nourishment. Having selected a target, the vine then performs a kind of cost-benefit calculation before deciding exactly how many coils it should invest—the more nutrients in the victim, the more coils it deploys. I asked Mancuso whether he was being literal or metaphorical in attributing intention to plants.

"Here, I'll show you something," he said. "Then you tell me if plants have intention." He swivelled his computer monitor around and clicked open a video.

Time-lapse photography is perhaps the best tool we have to bridge the chasm between the time scale at which plants live and our own. This example was of a young bean plant, shot in the lab over two days, one frame every ten minutes. A metal pole on a dolly stands a couple of feet away. The bean plant is "looking" for something to climb. Each spring, I witness the same process in my garden, in real time. I always assumed that the bean plants simply grow this way or that, until they eventually bump into something suitable to climb. But Mancuso's video seems to show that this bean plant "knows" exactly where the metal pole is long before it makes contact with it. Mancuso speculates that the plant could be employing a form of echolocation. There is some evidence that plants make low clicking sounds as their cells elongate; it's possible that they can sense the reflection of those sound waves bouncing off the metal pole.

The bean plant wastes no time or energy "looking"—that is, growing—anywhere but in the direction of the pole. And it is striving (there is no other word for it) to get there: reaching, stretching, throwing itself over and over like a fly rod, extending itself a few more inches with every cast, as it attempts to wrap its curling tip around the pole. As soon as contact is made, the plant appears to relax; its clenched leaves begin to flutter mildly. All this may be nothing more than an illusion of time-lapse photography. Yet to watch the video is to feel, momentarily, like one of the aliens in Mancuso's formative science-fiction story, shown a window onto a dimension of time in which these formerly inert beings come astonishingly to life, seemingly conscious individuals with intentions.

In October, I loaded the bean video onto my laptop and drove down to Santa Cruz to play it for Lincoln Taiz. He began by questioning its value as scientific data: "Maybe he has ten other videos where the bean didn't do that. You can't take one interesting variation and generalize from it." The bean's behavior was, in other words, an anecdote, not a phenomenon. Taiz also pointed out that the bean in the video was leaning toward the pole in the first frame. Mancuso then sent me another video with two perfectly upright bean plants that exhibited very similar behavior. Taiz was now intrigued. "If he sees that effect consistently, it would be exciting," he said—but it would not necessarily be evidence of plant intention. "If the phenomenon is real, it would be classified as a tropism," such as the mechanism that causes plants to bend toward light. In this case, the stimulus remains unknown, but tropisms "do not require one to postulate either intentionality or 'brainlike' conceptualization," Taiz said. "The burden of proof for the latter interpretation would clearly be on Stefano."

Perhaps the most troublesome and troubling word of all in thinking about plants is "consciousness." If consciousness is defined as inward awareness of oneself experiencing reality—"the feeling of what happens," in the words of the neuroscientist Antonio Damasio—then we can (probably) safely conclude that plants don't possess it. But if we define the term simply as the state of being awake and aware of one's environment—"online," as the neuroscientists say—then plants may qualify as conscious beings, at least according to Mancuso and Baluška. "The bean knows exactly what is in the environment around it," Mancuso said. "We don't know how. But this is one of the features of consciousness: You know your position in the world. A stone does not."

In support of their contention that plants are conscious of their environment, Mancuso and Baluška point out that plants can be rendered unconscious by the same anesthetics that put animals out: drugs can induce in plants an unresponsive state resembling sleep. (A snoozing Venus flytrap won't notice an insect crossing its threshold.) What's more, when plants are injured or stressed, they produce a chemical—ethylene—that works as an anesthetic on animals. When I learned this startling fact from Baluška in Vancouver, I asked him, gingerly, if he meant to suggest that plants could feel pain. Baluška, who has a gruff mien and a large bullet-shaped head, raised one eyebrow and shot me a look that I took to mean he deemed my question impertinent or absurd. But apparently not.

“If plants are conscious, then, yes, they should feel pain,” he said. “If you don’t feel pain, you ignore danger and you don’t survive. Pain is adaptive.” I must have shown some alarm. “That’s a scary idea,” he acknowledged with a shrug. “We live in a world where we must eat other organisms.”

Unprepared to consider the ethical implications of plant intelligence, I could feel my resistance to the whole idea stiffen. Descartes, who believed that only humans possessed self-consciousness, was unable to credit the idea that other animals could suffer from pain. So he dismissed their screams and howls as mere reflexes, as meaningless physiological noise. Could it be remotely possible that we are now making the same mistake with plants? That the perfume of jasmine or basil, or the scent of freshly mowed grass, so sweet to us, is (as the ecologist Jack Schultz likes to say) the chemical equivalent of a scream? Or have we, merely by posing such a question, fallen back into the muddied waters of "The Secret Life of Plants"?

Lincoln Taiz has little patience for the notion of plant pain, questioning what, in the absence of a brain, would be doing the feeling. He puts it succinctly: "No brain, no pain." Mancuso is more circumspect. We can never determine with certainty whether plants feel pain or whether their perception of injury is sufficiently like that of animals to be called by the same word. (He and Baluška are careful to write of "plant-specific pain perception.") "We just don't know, so we must be silent."

Mancuso believes that, because plants are sensitive and intelligent beings, we are obliged to treat them with some degree of respect. That means protecting their habitats from destruction and avoiding practices such as genetic manipulation, growing plants in monocultures, and training them in bonsai. But it does not prevent us from eating them. "Plants evolved to be eaten—it is part of their evolutionary strategy," he said. He cited their modular structure and lack of irreplaceable organs in support of this view.

The central issue dividing the plant neurobiologists from their critics would appear to be this: Do capabilities such as intelligence, pain perception, learning, and memory require the existence of a brain, as the critics contend, or can they be detached from their neurobiological moorings? The question is as much philosophical as it is scientific, since the answer depends on how these terms get defined. The proponents of plant intelligence argue that the traditional definitions of these terms are anthropocentric—a clever reply to the charges of anthropomorphism frequently thrown at them. Their attempt to broaden these definitions is made easier by the fact that the meanings of so many of these terms are up for grabs. At the same time, since these words were originally created to describe animal attributes, we shouldn't be surprised at the awkward fit with plants. It seems likely that, if the plant neurobiologists were willing to add the prefix "plant-specific" to intelligence and learning and memory and consciousness (as Mancuso and Baluška are prepared to do in the case of pain), then at least some of this "scientific controversy" might evaporate.

Indeed, I found more consensus on the underlying science than I expected. Even Clifford Slayman, the Yale biologist who signed the 2007 letter dismissing plant neurobiology, is willing to acknowledge that, although he doesn't think plants possess intelligence, he does believe they are capable of "intelligent behavior," in the same way that bees and ants are. In an e-mail exchange, Slayman made a point of underlining this distinction: "We do not know what constitutes intelligence, only what we can observe and judge as intelligent behavior." He defined "intelligent behavior" as "the ability to adapt to changing circumstances" and noted that it "must always be measured relative to a particular environment." Humans may or may not be intrinsically more intelligent than cats, he wrote, but when a cat is confronted with a mouse its behavior is likely to be demonstrably more intelligent.

"Those who ignore history are entitled to repeat it."

Slayman went on to acknowledge that "intelligent behavior could perfectly well develop without such a nerve center or headquarters or director or brain—whatever you want to call it. Instead of 'brain,' think 'network.' It seems to be that many higher organisms are internally networked in such a way that local changes," such as the way that roots respond to a water gradient, "cause very local responses which benefit the entire organism." Seen that way, he added, the outlook of Mancuso and Trewavas is "pretty much in line with my understanding of biochemical/biological networks." He pointed out that while it is an understandable human prejudice to favor the "nerve center" model, we also have a second, autonomic nervous system governing our digestive processes, which "operates most of the time without instructions from higher up." Brains are just one of nature's ways of getting complex jobs done, for dealing intelligently with the challenges presented by the environment. But they are not the only way: "Yes, I would argue that intelligent behavior is a property of life."

To define certain words in such a way as to bring plants and animals beneath the same semantic umbrella—whether of intelligence or intention or learning—is a philosophical choice with important consequences for how we see ourselves in nature. Since "The Origin of Species," we have understood, at least intellectually, the continuities among life's kingdoms—that we are all cut from the same fabric of nature. Yet our big brains, and perhaps our experience of inwardness, allow us to feel that we must be fundamentally different—suspended above nature and other species as if by some metaphysical "skyhook," to borrow a phrase from the philosopher Daniel Dennett. Plant neurobiologists are intent on taking away our skyhook, completing the revolution that

Darwin started but which remains—psychologically, at least—incomplete.

"What we learned from Darwin is that competence precedes comprehension," Dennett said when I called to talk to him about plant neurobiology. Upon a foundation of the simplest competences—such as the on-off switch in a computer, or the electrical and chemical signalling of a cell—can be built higher and higher competences until you wind up with something that looks very much like intelligence. "The idea that there is a bright line, with real comprehension and real minds on the far side of the chasm, and animals or plants on the other—that's an archaic myth." To say that higher competences such as intelligence, learning, and memory "mean nothing in the absence of brains" is, in Dennett's view, "cerebrocentric."

All species face the same existential challenges—obtaining food, defending themselves, reproducing—but under wildly varying circumstances, and so they have evolved wildly different tools in order to survive. Brains come in handy for creatures that move around a lot; but they're a disadvantage for ones that are rooted in place. Impressive as it is to us, self-consciousness is just another tool for living, good for some jobs, unhelpful for others. That humans would rate this particular adaptation so highly is not surprising, since it has been the shining destination of our long evolutionary journey, along with the epiphenomenon of self-consciousness that we call "free will."

In addition to being a plant physiologist, Lincoln Taiz writes about the history of science. "Starting with Darwin's grandfather, Erasmus," he told me, "there has been a strain of teleology in the study of plant biology"—a habit of ascribing purpose or intention to the behavior of plants. I asked Taiz about the question of "choice," or decision-making, in plants, as when they must decide between two conflicting environmental signals—water and gravity, for example.

"Does the plant decide in the same way that we choose at a deli between a Reuben sandwich or lox and bagel?" Taiz asked. "No, the plant response is based entirely on the net flow of auxin and other chemical signals. The verb 'decide' is inappropriate in a plant context. It implies free will. Of course, one could argue that humans lack free will too, but that is a separate issue."

I asked Mancuso if he thought that a plant decides in the same way we might choose at a deli between a Reuben or lox and bagels.

"Yes, in the same way," Mancuso wrote back, though he indicated that he had no idea what a Reuben was. "Just put ammonium nitrate in the place of Reuben sandwich (whatever it is) and phosphate instead of salmon, and the roots will make a decision." But isn't the root responding simply to the net flow of certain chemicals? "I'm afraid our brain makes decisions in the same exact way."

"Why would a plant care about Mozart?" the late ethnobotanist Tim Plowman would reply when asked about the wonders catalogued in "The Secret Life of Plants." "And even if it did, why should that impress us? They can eat light, isn't that enough?"

One way to exalt plants is by demonstrating their animal-like capabilities. But another way is to focus on all the things plants can do that we cannot. Some scientists working on plant intelligence have questioned whether the "animal-centric" emphasis, along with the obsession with the term "neurobiology," has been a mistake and possibly an insult to the plants. "I have no interest in making plants into little animals," one scientist wrote during the dustup over what to call the society. "Plants are unique," another wrote. "There is no reason to . . . call them demi-animals."

When I met Mancuso for dinner during the conference in Vancouver, he sounded very much like a plant scientist getting over a case of "brain envy"—what Taiz had suggested was motivating the plant neurologists. If we could begin to understand plants on their own terms, he said, “it would be like being in contact with an alien culture. But we could have all the advantages of that contact without any of the problems—because it doesn’t want to destroy us!” How do plants do all the amazing things they do without brains? Without locomotion? By focussing on the otherness of plants rather than on their likeness, Mancuso suggested, we stand to learn valuable things and develop important new technologies. This was to be the theme of his presentation to the conference, the following morning, on what he called “bioinspiration.” How might the example of plant intelligence help us design better computers, or robots, or networks?

Mancuso was about to begin a collaboration with a prominent computer scientist to design a plant-based computer, modelled on the distributed computing performed by thousands of roots processing a vast number of environmental variables. His collaborator, Andrew Adamatzky, the director of the International Center of Unconventional Computing, at the University of the West of England, has worked extensively with slime molds, harnessing their maze-navigating and computational abilities. (Adamatzky’s slime molds, which are a kind of amoeba, grow in the direction of multiple food sources simultaneously, usually oat flakes, in the process computing and remembering the shortest distance between any two of them; he has used these organisms to model transportation networks.) In an e-mail, Adamatzky said that, as a substrate for biological computing, plants offered both advantages and disadvantages over slime molds. "Plants are more robust," he wrote, and "can keep their shape for a very long time," although they are slower-growing and lack the flexibility of slime molds. But because plants are already "analog electrical computers," trafficking in electrical inputs and outputs, he is hopeful that he and Mancuso will be able to harness them for computational tasks.

"You haven't seen security till you've seen it on the iPad 2."

Mancuso was also working with Barbara Mazzolai, a biologist-turned-engineer at the Italian Institute of Technology, in Genoa, to design what he called a "plantoid": a robot designed on plant principles. "If you look at the history of robots, they are always based on animals—they are humanoids or insectoids. If you want something swimming, you look at a fish. But what about imitating plants instead? What would that allow you to do? Explore the soil!" With a grant from the European Union's Future and Emerging Technologies program, their team is developing a "robotic root" that, using plastics that can elongate and then harden, will be able to slowly penetrate the soil, sense conditions, and alter its trajectory accordingly. "If you want to explore other planets, the best thing is to send plantoids."

The most bracing part of Mancuso's talk on bioinspiration came when he discussed underground plant networks. Citing the research of Suzanne Simard, a forest ecologist at the University of British Columbia, and her colleagues, Mancuso showed a slide depicting how trees in a forest organize themselves into far-flung networks, using the underground web of mycorrhizal fungi which connects their roots to exchange information and even goods. This "wood-wide web," as the title of one paper put it, allows scores of trees in a forest to convey warnings of insect attacks, and also to deliver carbon, nitrogen, and water to trees in need.

When I reached Simard by phone, she described how she and her colleagues track the flow of nutrients and chemical signals through this invisible underground network. They injected fir trees with radioactive carbon isotopes, then followed the spread of the isotopes through the forest community using a variety of sensing methods, including a Geiger counter. Within a few days, stores of radioactive carbon had been routed from tree to tree. Every tree in a plot thirty metres square was connected to the network; the oldest trees functioned as hubs, some with as many as forty-seven connections. The diagram of the forest network resembled an airline route map.

The pattern of nutrient traffic showed how “mother trees” were using the network to nourish shaded seedlings, including their offspring—which the trees can apparently recognize as kin—until they’re tall enough to reach the light. And, in a striking example of interspecies coöperation, Simard found that fir trees were using the fungal web to trade nutrients with paper-bark birch trees over the course of the season. The evergreen species will tide over the deciduous one when it has sugars to spare, and then call in the debt later in the season. For the forest community, the value of this coöperative underground economy appears to be better over-all health, more total photosynthesis, and greater resilience in the face of disturbance.

In his talk, Mancuso juxtaposed a slide of the nodes and links in one of these subterranean forest networks with a diagram of the Internet, and suggested that in some respects the former was superior. "Plants are able to create scalable networks of self-maintaining, self-operating, and self-repairing units," he said. "Plants."

As I listened to Mancuso limn the marvels unfolding beneath our feet, it occurred to me that plants do have a secret life, and it is even stranger and more wonderful than the one described by Tompkins and Bird. When most of us think of plants, to the extent that we think about plants at all, we think of them as old—holdovers from a simpler, prehuman evolutionary past. But for Mancuso plants hold the key to a future that will be organized around systems and technologies that are networked, decentralized, modular, reiterated, redundant—and green, able to nourish themselves on light. "Plants are the great symbol of modernity." Or should be: their brainlessness turns out to be their strength, and perhaps the most valuable inspiration we can take from them.

At dinner in Vancouver, Mancuso said, "Since you visited me in Florence, I came across this sentence of Karl Marx, and I became obsessed with it: 'Everything that is solid melts into air.' Whenever we build anything, it is inspired by the architecture of our bodies. So it will have a solid structure and a center, but that is inherently fragile. This is the meaning of that sentence—'Everything solid melts into air.' So that's the question: Can we now imagine something completely different, something inspired instead by plants?” ♦