# Ants, plants and antibiotics

**Ted R. Schultz**

**The partnership between ants and their fungal gardens has a newly discovered third member — a bacterium, which grows on the ants' bodies and produces antibiotics to kill a parasite that infects their crops.**

Roughly 50 million years ago in South America, a lone species of ant abandoned its primitive hunter–gatherer ways and, in a unique event in ant evolution, adopted an agrarian lifestyle. Entering into a partnership with a parasol mushroom, these agricultural pioneers learned to weed, manure and propagate their fungal crops, ensuring a reliable source of food. From this innovative ancestral stock arose the ant group Attini, of which there are now about 210 species, largely concentrated in wet, South American forests.

The Attini include the well-known leaf-cutting ants, in which the association (or 'symbiosis') between ants and fungi has become enormously successful. Colonies of some *Atta* species may contain eight million ants, with the collective biomass of an adult cow. These ants cut a cow's daily requirement of fresh vegetation, but they do not directly consume it. Instead, by chewing it into a pulp, they convert the vegetation into a substrate on which their fungal crops are grown. The fungus, in turn, produces specialized structures known as gongylidia, which serve as food for the ants. This arrangement has been called an “unholy alliance”[1], because it combines the ants' ability to circumvent plant antifungal defences (such as the waxy coatings of leaves, which the ants scrape away) with the ability of the fungus to subvert plant anti-insect defences (such as chemical insecticides, which are digested by the fungus, so are absent from the fungal tissue consumed by the ants).

The leaf-cutters have been known since earliest times — they are mentioned, for instance, in the Popul Vuh, the creation myth of the Central American Mayan civilization (300–900 AD). But the reason for cutting leaves was long misunderstood. In 1863, the British naturalist H. W. Bates incorrectly asserted[2] that “the leaves are used to thatch the domes which cover the entrances to [the ants'] subterranean dwellings, thereby protecting from the deluging rains the young broods in the nests beneath”. The surprising truth was finally deduced by the naturalist and mining engineer Thomas Belt. In 1874 he wrote[3]: “I believe the real use [the ants] make of [the leaves] is as a manure, on which grows a minute species of fungus, on which they feed; that they are, in reality, mushroom growers and eaters”. Belt's revelation (which was independently discovered that same year by Fritz Müller[4]) marks the beginning of scientific studies into non-human agricultural symbiosis. But it now seems that biologists have vastly underestimated the true extent of this association. Instead of the commonly accepted two-part symbiosis between ant and fungus, Currie and colleagues[5] report in last week's *Nature* that the attine symbiosis actually consists of three partners from three separate kingdoms — ant, fungus and antibiotic-producing bacterium — as well as a parasitic fungal 'weed' that infects attine gardens (Fig. 1).

Attine fungal crops are usually propagated from existing gardens. A foundress ant queen carries a small pellet of fungus from her mother's nest in her mouth. When she founds a new nest, she uses this pellet to start her new garden. Such vegetative (or clonal) propagation from one generation to the next suggests that these ancient crops have strictly coevolved with their ant hosts. But phylogenetic and population-genetic studies of attine ants[6,7] and fungi[8,9] support an alternative picture, at least in the 'lower' Attini, which do not cut leaves. Here, ant colonies occasionally replace their clonal crops with free-living fungi acquired from outside the nest. Colonies also replace their resident fungi with crops obtained from other ants, so even distantly related ant species may sometimes share the same garden clone. The best long-term evolutionary strategy for most ant farmers seems to be cultivating a diversity of crops, rather than committing exclusively to a single one.

Such a strategy makes sense in the face of shifting environmental pressures, and Currie and colleagues[5] have now identified a particularly important source of such pressure — a group of closely related, highly specialized parasites in the fungal genus *Escovopsis*[10,11], which infect the ants' fungal gardens. This is an ancient association — *Escovopsis* parasite species are found in gardens of just about all species of fungus-growing ants, but not, so far, in any other habitat. They are not transmitted from the parental to offspring nest; instead, they must infect every new generation of gardens from the outside, probably by hitchhiking on the ants' bodies. Once inside, the *Escovopsis* parasite bides its time at low frequency. But, like many other pathogens that are highly adapted to their hosts (including some human diseases), when the health of the garden is compromised, the parasite becomes virulent,

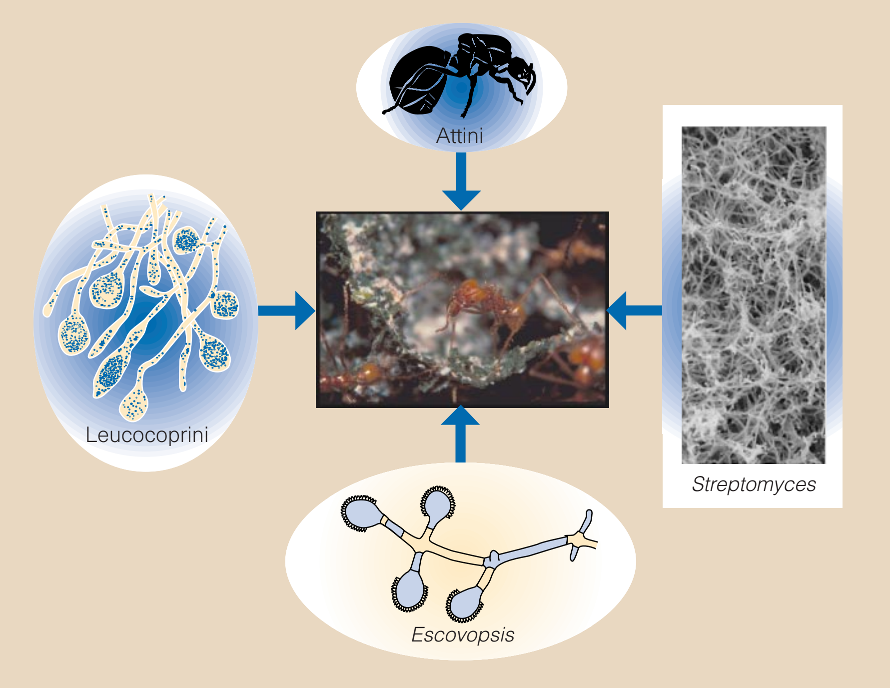

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Figure 1 **Ants use antibiotics to control garden pests. The attine ant cultivates a mushroom from the fungal tribe Leucocoprini as a source of food. Currie *et al.*[5] now show that there is another partner in this mutually beneficial relationship — a bacterium from the genus *Streptomyces*. This bacterium produces antibiotics to prevent infestation of the ant garden by the parasite *Escovopsis*, which is itself also a fungus.**

overgrowing and destroying the fungal crop in a short period of time.

In healthy gardens, Currie *et al.* show that *Escovopsis* is held in check by specific antibiotics produced by bacteria living on the bodies of the ants. It seems hardly a coincidence that these bacteria belong to the genus *Streptomyces*, from which over half of the antibiotics used by humans are derived. Like the parallels between ant and human agriculture[9], understanding this use of antibiotics by ants could be directly relevant to human survival. For example, whereas humans have been using antibiotics for fewer than 60 years (longer if you consider the medicinal use of moulds in the ancient Far East, or among the Greeks and Romans), ants have been using them for 50 million years. Given that rapidly evolving pathogen resistance seems to be outpacing human antibiotic development, we might ask how the attine antibiotics have remained effective against the fungus-garden pathogens for such a long time.

The answer probably involves an evolutionary 'arms race', in which garden pathogens and antibiotic bacteria (as well as fungal crops and ants) have evolved in tandem down various evolutionary pathways. The result is the particular assemblages of ants, fungi and bacteria that we encounter today. To understand how these assemblages came to be, we need to reconstruct and reconcile the evolutionary histories of each participant. Ideally, we also need to identify the closest free-living relative of the attine bacteria (probably an inhabitant of South American soils) and of the garden parasites (possibly a pathogen of free-living fungi).

Given the usefulness of the attine system as a model for symbiotic evolution[1,8,9,12,13] and the parallels between ants and humans, a comparative biological study within an evolutionary–historical framework may reward us with theoretical insights into symbiotic evolution, as well as with practical insights for such diverse fields as medicine and agriculture. But none of these rewards will be realized unless we conserve the rapidly declining rainforests, which are home to these irreplaceable end-products of vast spans of evolutionary time. □

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**Quantum computation**

# Solid-state qubits under control

**D. V. Averin**

One of the most significant developments in physics during the past 20 years is the clear and convincing proof that macroscopic systems, such as a superconductor with billions of electrons in it, can behave quantum mechanically. This conclusion changes the view, which was established in the early days of quantum mechanics, that there is a fundamental difference between the microscopic systems that obey quantum mechanics and the macroscopic world of classical physics. This has important implications for the conceptual foundations of quantum theory[1], in particular quantum measurement theory, which is frequently described in terms of the separation of the microscopic object and the macroscopic measuring device.

The most fundamental demonstration of quantum mechanics at the macroscopic level would be the coherent superposition of two distinct quantum states, which is a purely quantum effect and has no classical analogue. This effect also has implications for quantum computing, because a quantum two-state system represents a single quantum bit, or qubit, which is the elementary building block of a quantum computer. Superposition of information states in qubits should make quantum computers fundamentally more powerful than classical computers, a prospect that attracts the interest of computer scientists and physicists, as well as government agencies. As part of a quantum computer, macroscopic qubits would have the advantage of being more manageable than their microscopic counterparts.

For a long time macroscopic quantum coherence remained elusive, despite observations of other macroscopic quantum effects[2,3]. On page 786 of this issue, Nakamura *et al.*[4] report an important step towards its realization. The authors provide convincing evidence of quantum superposition of the two charge states of a 'single-Cooper-pair box' (see Box 1) by observing coherent oscillations between these states. Although the coherent quantum superposition of charge states was implied by several previous experiments[5–9], this is the first time it has been observed directly. The audaciously simple idea behind the experiment is to align the energy levels of a Cooper pair (two electrons bound together in a superconductor) in the two electrodes of the Cooper-pair box using a voltage pulse of about 100 ps. When the levels are aligned, the Cooper pair starts to oscillate back and forth between the electrodes, and the oscillations are detected by monitoring one of the electrodes.

The question of whether the observed quantum coherence of the charge states is macroscopic or not is debatable in much the same way as the question of how many grains of sand are needed to form a sandpile. On the one hand, a Cooper-pair box has all the attributes of a macroscopic system. It consists of billions of atoms and the parameters of its charge states, most importantly their energies, are defined by the collective motion of the billions of electrons in the junction electrodes, and can easily be controlled by external signals. For instance, the charging energy depends on the geometric capacitance of the box, which reflects the collective screening properties of the electron gas in the box electrodes. Similarly, the amplitude of Cooper-pair tunnelling depends on contributions from each of the electrons in the box. This all points to an interpretation of the quantum coherence of charge states in the Cooper-pair box as macroscopic. On the other hand, the two charge states forming the coherent superposition differ in charge by only one Cooper pair. One Cooper pair tunnelling between these two states is identical to one electron tunnelling between two localized states, which is clearly a microscopic process. Because of this contradiction between the microscopic and macroscopic aspects of coherence of the charge states in the box system, it is probably appropriate to interpret this effect as 'mesoscopic' quantum coherence.

Besides its significance in the context of macroscopic quantum phenomena, Nakamura and co-workers' experiment[4] also demonstrates a practical solid-state qubit for quantum computation. At present, there is an intensive search for realistic approaches to the problem of building a quantum computer. Despite impressive progress achieved in this direction by NMR spectroscopy of organic molecules in solutions[10,11], it seems to be impossible to scale up the few qubit gates provided by the NMR technique for a practical solution to the problem. In contrast, solid-state structures offer a much greater degree of control over design and fabrication, necessary for constructing larger-scale devices.

Several possible implementations of