the mobile spins need to be transferred efficiently across interfaces between different semiconductor materials. Because such interfaces are ubiquitous in complex electronic devices, this transfer must proceed without appreciable loss of spin polarization. Third, once the spins are transferred into the heart of a device, where the switching or memory function actually occurs, their polarization must be preserved long enough for the desired operation to be carried out.

Progress towards satisfying these prerequisites has been made just within the past few years. Semiconductors that are not normally magnetic, such as gallium arsenide, have been turned into ferromagnetic materials by adding magnetic dopants[3–5]. Some of these new materials remain ferromagnetic even at relatively high temperatures. Crucially, their compatibility with conventional non-magnetic semiconductors enables optimal interfaces to be constructed in all-semiconductor spintronic devices. This allows spin-polarized electrons to be transferred efficiently between the respective material layers. This has clearly been demonstrated by the recent success of spintronics-based light-emitting diodes, which use electrical spin injection to emit circularly polarized light[6–8]. Optical techniques have been used to excite spins in doped semiconductors. In a magnetic field these spins continuously precess (rotate) about the field. The important point is that this precession has been observed to persist coherently for surprisingly long periods of time[9].

These are promising starts, yet not all of the pieces are in place. For example, efficient electrical injection (transfer) of spins across interfaces has, so far, only been demonstrated in structures involving semi-magnetic materials[6,8], which provide spin-polarized electrons solely when subjected to very high magnetic fields, that is, at levels available only in the laboratory from superconducting magnets. By contrast, when electrons from a ferromagnetic superconductor, which have intrinsic spin polarization even in the absence of an external field, are electrically injected from a ferromagnetic semiconductor across an interface into another non-magnetic semiconductor, the results to date are much less pronounced. Although the demonstration under these conditions is an important achievement in itself, the efficiency attained so far is only a few per cent[7].

Malajovich and co-workers[2] have now shown that spin-transfer efficiency can be increased by up to a factor of 40 by using electric fields to 'drag' spins across a semiconductor interface. The authors first use a laser pulse at the right frequency to create a long-lived reservoir of spin-polarized carriers, here in gallium arsenide, and then, in two separate experiments, show that both externally applied and built-in electric fields can be highly effective at transferring spins from this reservoir to another semiconductor, here zinc selenide (Fig. 1). In the latter case, internal built-in electric fields are created by the explicit inclusion of electrical dopants of different polarities in the semiconductor layers. In this way, a 'natural' potential arises at the interface between the differently doped semiconductors; this forms the basis for semiconductor diodes.

Electrons in solids have different spin properties to those in a vacuum. The electron's magnetic properties (and therefore its spin) are quantified in terms of a '*g*-factor', which characterizes the electron's energy in a magnetic field. One of the intriguing aspects of the new work is that, under the best spin-transfer conditions, the entire population of transferred spins (within the collecting layer) is found to behave, overall, with the character of their original environment — in this case the original semiconductor reservoir.

This occurs because of a newly identified, persistent mode of spin transfer, which makes the reservoir act, in effect, as a spin 'battery'. This means that, under special conditions, a spin reservoir can be made to continuously source a spin-polarized current across the interface until the reservoir itself is depleted.

This is demonstrated by Malajovich *et al.*[2] using a sensitive technique that allows them to interrogate the identity (effective *g*-factor) of the ensemble of transferred spins. They find that the effective *g*-factor for the population of transferred spins can be continuously metamorphosed from a value characteristic of the spin reservoir to that of the collecting semiconductor. The precise behaviour depends on the strength of the effective electric field. This unexpected phenomenon may provide the basis for what the authors call multifunctional spintronic devices, in which the character of the spin currents can be controlled by both electric and magnetic fields. This prospect injects an intriguing new 'spin' into the emerging technology of semiconductor spintronics. ■

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Plant microbiology

Quieting the raucous crowd

Jared R. Leadbetter

Many bacteria communicate by using dedicated signalling molecules. Signal-degrading enzymes from other bacteria interrupt the conversation, and can protect tobacco and potato plants from infection.

Most of us have had occasion to reach into a refrigerator crisper drawer to sponge out the remnants of a wilted, slimy head of lettuce. One of the major culprits of this horror is *Erwinia*, a bacterium that also causes economically important wilts and soft-rots of crops. On page 813 of this issue, Dong and colleagues[1] introduce a promising new way of controlling *Erwinia* infections — an approach that might also have implications for treating some human diseases.

The past 30 years have seen the discovery that *Erwinia* and many other bacteria can not only sense, but also respond to, increases in their population density. When crowded, they dramatically change their physiology. This process, called quorum sensing, is often associated with the bacteria shifting from a free-living lifestyle to becoming dependent on a particular host[2]. Many of these bacteria produce, monitor and respond to the accumulation of soluble signalling molecules — quorum-sensing signals. Molecules in one class of these signals have a specific chemical structure described as an acyl-homoserine lactone (AHL; Fig. 1). In the case of *Erwinia*, AHLs activate the expression of diverse 'virulence factors' such as slime, and enzymes that solubilize polysaccharides[3,4] to provide the bacteria with nutrients.

Dong *et al.*[1] took advantage of *Erwinia*'s quorum-sensing signals to develop a new way of controlling quorum-regulated processes. They call their technique 'quorum quenching'. Instead of trying to target bacterial growth or viability directly, the authors focused on ways to degrade the AHL signals as they are produced, with the aim of reducing or eliminating the expression of quorum-regulated virulence factors. To do this, Dong *et al.* constructed transgenic tobacco and potato plants expressing the bacterial gene *aiiA*. This gene encodes an enzyme that renders AHLs biologically inactive. Remarkably, the transgenic plants became resistant to *Erwinia* infection, even when unrealistically high numbers of *Erwinia* cells were introduced into wounded tissues. In rare cases where there were localized signs of disease, the transgenic plants managed to fight off the infection over time. By comparison, control plants succumbed to an uncontrol-

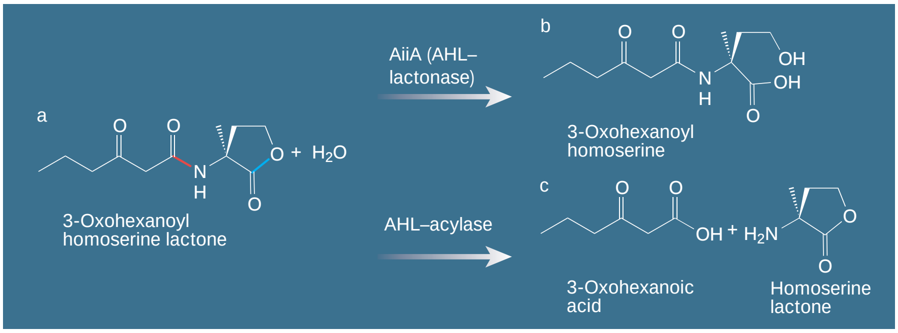

Figure 1 **Disabling soft rot: biochemical routes to the inactivation of acyl-homoserine lactone (AHL) molecules.** a, **The AHL *N*-3-oxohexanoyl-L-homoserine lactone is a quorum-sensing signal used by the *Erwinia* bacteria, which cause soft rot in certain crops, to control their ability to cause disease in plants. The bonds that can be broken by two inactivating enzymes are shown in blue and red.** b, **Dong *et al.*[1] have used the protein AiiA to hydrolyse the blue bond and generate the inactivated signal *N*-3-oxohexanoyl-L-homoserine.** c, **3-Oxohexanoic acid and L-homoserine lactone are the products of an uncharacterized AHL-acylase found in the bacterium *Variovorax paradoxus*.**

lable infection, even when challenged with comparatively low numbers of bacteria.

The result is a triumph for the approach of mining bacterial metabolic diversity for applied uses. In this case, Dong *et al.* capitalized on the discovery that many bacteria can degrade, and so inactivate, AHLs. Earlier, the same group[5] had isolated hundreds of bacterial species from soil and screened them for the ability to degrade AHLs. From this collection, a bacterium of the genus *Bacillus* was identified as being especially promising. It was from this strain that *aiiA* was cloned. As well as their exciting observations of plants expressing this gene, the authors[1] also show how the AiiA protein inactivates AHL signals: it degrades the molecule's lactone ring, so acting as an AHL-lactonase (Fig. 1).

Another soil bacterium has been identified that also degrades these signals, through an uncharacterized AHL-acylase activity[6]. Clearly, there are different mechanisms for the biodegradation of AHLs, inviting comparisons to the way in which penicillins can be inactivated.

Enzymes that degrade AHLs might be useful in controlling many other quorum-sensing bacterial populations, such as biofilms. These are dense populations of bacteria, attached to some surface, that grow to form complex, tissue-like structures; they are extremely resistant to antibiotics and have been implicated in many human diseases[7]. For example, the formation of biofilms by *Pseudomonas aeruginosa* is common in the lungs of people with cystic fibrosis. Here, quorum sensing regulates the expression of virulence factors and the development of biofilms[8]. As aerosols of mucous-degrading enzymes and other chemicals are already used to treat lung disease in cystic fibrosis patients, it might prove fruitful to add AHL-degrading enzymes to the mix.

But in the rush to develop products based on AHL-lactonases that will no doubt come, microbiologists should not lose sight of the significance of AHL-degrading enzymes to the physiology and ecology of the bacteria that produce them. There are questions to be answered, such as: do these enzymes have narrow or broad substrate specificity? And how are they regulated in the cell?

Moreover, what is the effect of signal degradation on the cells involved, and in the environment at large? No doubt bacteria have a stake in disarming the quorum-sensing systems of other species. For example, *Erwinia* regulates its synthesis of carbapenem, an antibacterial compound, through AHL-dependent mechanisms. Presumably, carbapenem keeps other bacteria away from the nutrient cache accumulated during plant infection. Those other species may use signal degradation to circumvent such a barrier. As revealed by genome sequencing, nearly identical counterparts of *aiiA* are present in several *Bacillus* species. Curiously, though, the quorum-sensing plant pathogen *Agrobacterium tumefaciens* may also have an *aiiA* relative, called *attM*, which is associated with genetic loci that encode proteins needed for this bacterium to colonize plant roots[9]. It is not yet clear why *Agrobacterium*, which makes and responds to AHL signals, might also need to degrade them.

Studies of the complex competitive interactions among microbes will no doubt be very informative. One epic story of microbial rivalry encompasses counter-evolutionary tales of naturally occurring β-lactam antibiotics, the enzymes that degrade them (β-lactamases) and β-lactamase inhibitors, such as clavulanic acid. In a parallel to this narrative, bacteria that make AHLs may have evolved resistance to the enzymes that break the signals. Some bacteria might produce factors that bind and block the active sites of AHL-degrading enzymes. Others might have evolved enzymes that recycle the signals after hydrolysis of their lactone rings. Nature throws punches and counter-punches: it will surely be both interesting and useful to investigate and anticipate them. In the meantime, Dong *et al.*[1] have returned *Erwinia*'s first blow. In doing so, they have revealed a soft spot in soft-rot diseases, perhaps of a type to be found in other quorum-sensing pests and pathogens. ■

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Carbon cycle

The roots of the matter

F. Stuart Chapin III and Roger W. Ruess

Perhaps the most scientifically challenging phase of the terrestrial carbon cycle occurs below ground. Innovative experiments, carried out in northern Sweden, illustrate the huge influence of roots and associated fungi.

Photosynthesis by terrestrial vegetation accounts for about half of the carbon that annually cycles between Earth and the atmosphere[1]. Although above-ground plant production is relatively well documented from field measurements and globally distributed satellite observations, the quantity of carbon that plants transfer below ground is not well known. Microvideo cameras provide direct observations of the growth, longevity and decomposition of fine roots[2,3]. However, other large components of below-ground plant production, such as exudation of organic compounds by roots and transfer of carbohydrates to associated mycorrhizal fungi, are difficult to study non-destructively and have not been estimated. Estimates of the contribution of root respiration to total CO_2 efflux from soil range from 10% to 90%, with methodological uncertainties accounting for most of this variation[4].

On page 789 of this issue, Högberg and colleagues[5] present a new approach that