transmission dynamics[5]. These studies not only provided well defined estimates of ecological parameters, but also identified an essential ingredient in outbreak dynamics, namely that gypsy moth larvae vary greatly in their susceptibility to the virus. Heterogeneity of this form has a known stabilizing effect and is a crucial contributing factor in ensuring the recurrence of outbreaks. Dwyer and colleagues' model takes this heterogeneity into account, along with the essential time delays that occur between larval infection and actual death, as well as inter-epidemic dynamics such as pathogen survival from one season to the next, and differences in mean susceptibility among larval stages. The version of the model analysed here is, in fact, the 'infinite epidemic/burnout approximation' of a more sophisticated set of equations[5], but it elegantly captures all the main features.

Dwyer *et al.* note that their host–pathogen model inherits the multiple equilibria of the 1970s models. But, in addition, it generates even more complex, and sometimes chaotic, dynamics. With the inclusion of environmental stochasticity, to mimic the effects of weather, the model population jumps unpredictably between multiple attractors (different nonequilibrium 'attracting' states), producing time series of changes in population density that closely resemble those of real gypsy moth populations. Model outbreaks occur on average every 11 years, but with a variability from outbreak to outbreak that closely matches real data. Between outbreaks, the predator maintains the model gypsy moth population at relatively low levels. With time and stochasticity, however, the population slowly builds up to trigger the next outbreak. On inclusion of spatial structure, the authors show that different subpopulations synchronize their chaotic outbreak oscillations and remain relatively in phase with one another, which is in keeping with the coupled oscillator theory from nonlinear dynamics[6]. This result helps to explain the enigmatic spatial synchronization of many pest species.

Now that Dwyer *et al.*[2] have exposed the critical mechanisms behind gypsy moth outbreaks, it would be interesting to take their work further. For example, the model would allow assessment of the relatively new and effective natural enemy of the gypsy moth, the fungal pathogen *Entomophaga maimaiga*, present in North America since 1989. Unlike NPV, which triggers the collapse of a gypsy moth outbreak, the fungus can sometimes prevent outbreaks altogether. In some areas of North America, *E. maimaiga* has the potential to bring gypsy moth damage to a halt. Modelling work (see, for example, ref. 7) is currently under way to assess the dispersal dynamics of the fungus, its ability to become established and its overall impact. Modifications of Dwyer and colleagues' model might help in this regard. Their model will undoubtedly prove of great value for studying the dynamics of many other pest species that cause episodes of ecological devastation. ■

Lewi Stone is in the Biomathematics Unit, Department of Zoology, Tel Aviv University, Ramat Aviv 69978, Israel.
e-mail: lew521@yahoo.com

1. Liebhold, A., Mastro, V. & Schaefer, P. W. *Bull. Entomol. Soc. Am.* **35,** 20–21 (1989).
2. Dwyer, G., Dushoff, J. & Yee, S. H. *Nature* **430,** 341–345 (2004).
3. Myers, J. H. *Adv. Ecol. Res.* **18,** 179–242 (1988).
4. Elkinton, J. S. & Liebhold, A. M. *Annu. Rev. Entomol.* **35,** 571–596 (1990).
5. Dwyer, G., Dushoff, J., Elkinton, J. S. & Levin, S. A. *Am. Nat.* **156,** 105–120 (2000).
6. Blasius, B., Huppert, A. & Stone, L. *Nature* **399,** 354–359 (1999).
7. Weseloh, R. M. *Biol. Control* **29,** 138–144 (2004).

Imaging techniques

Seeing single spins

P. Chris Hammel

Combining the imaging power of magnetic resonance and the sensitivity of atomic force microscopy has created a hybrid technique that can resolve single spins beneath the surface of a sample.

Magnetic resonance imaging (MRI) and atomic force microscopy (AFM) are two of the most powerful imaging technologies available. MRI can provide, non-invasively, fully three-dimensional images from deep within an object. However, the spatial resolution of this technique is limited to the smallest volume that contains enough nuclear or electronic spins to generate a detectable signal. Sensitivity to a smaller number of spins is the key to improving spatial resolution.

Combining three-dimensional MRI with the excellent force sensitivity of AFM — in magnetic resonance force microscopy, or MRFM — opens the possibility of performing scanned-probe MRI with much improved spatial resolution. On page 329 of this issue, Rugar *et al.*[1] report the combination of MRI and AFM to achieve sensitivity to a single electron spin. Compare this with the 10^8–10^{10} spins required in a conventional electron-spin resonance experiment. This signal achievement will dramatically alter the horizons for high-resolution imaging.

But the ability to detect individual spins is about more than imaging — it implies the power to manipulate individual spins as well. Present-day information processing relies on the electron's charge, through manipulating and detecting voltages in electronic circuits. Exploiting the electron's magnetic moment, or spin, could lead to significant enhancements in electronic information processing, including nonvolatile memory, increased integration densities and reduced power consumption[2]. Furthermore, the spin of the electron is a natural two-state quantum system ('qubit') for quantum computing; the spin can also be isolated from its physical environment to achieve the long decoherence times needed for successful computation.

MRI exploits the proportionality between the easily measured frequency of a magnetic resonance signal and the value of the magnetic field at the spin's location. In an applied magnetic field, the resonant frequency of spins increases steadily across a region, following the increasing field. Thus measuring the resonant frequency pinpoints the location of the spins responsible for the signal. And because magnetic fields penetrate samples easily, three-dimensional images can be constructed from signals from deep inside them. MRI has had a huge impact in the biomedical arena, but there is continuing demand for higher spatial resolution, below the 1 mm^3 currently achievable in medical settings.

A decade ago, John Sidles proposed[3] a radical approach to MRI, based on detecting the force exerted by the spins in a sample on a microscopic magnet, which is mounted on a flexible cantilever above the sample. This would offer the much improved sensitivity needed to reduce the imaged volume and to achieve atomic-scale nuclear MRI[4]. Rugar and colleagues' demonstration[1] of single electron-spin detection using Sidles' approach is a heartening milestone in realizing the dream of high-resolution MRI. Two elements are essential for the dramatically improved sensitivity: large magnetic-field gradients generated by micrometre-scale magnetic probe tips, and highly sensitive cantilevers. Rugar *et al.* engineered cantilevers with a state-of-the-art force sensitivity[5] of 10^{-18} newtons specifically for this purpose.

The micromagnetic probe mounted on the cantilever tip generates a large field gradient (approximately proportional to its magnetization divided by its diameter). In this set-up[1] (Fig. 1), the gradient of the microscopic magnetic probe was approximately 2 gauss per nanometre, so that the force generated on the cantilever by an individual electron-spin was detectable, at 2×10^{-18} newtons. The field gradient has a second, independent role: as in MRI, it causes spins located at different depths beneath the micromagnetic tip to resonate at different

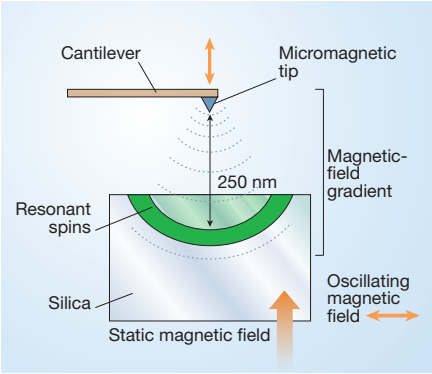

Figure 1 **Magnetic resonance force microscopy. A micromagnetic tip is mounted on a specially engineered cantilever above a silica sample containing a low density of electron spins. In the presence of the large field gradient of the tip, the applied oscillating magnetic field excites electron spins at a particular depth in the sample at their resonant frequency. The force exerted by a single electron through its magnetic moment on the cantilever, although only at the level of 10^{-18} newtons, can be detected — as shown by Rugar *et al.*[1], who have used this technique to achieve the detection of a single electron spin.**

frequencies; this provides the basis for selective excitation of spins, and hence imaging. Among scanned-probe techniques, MRFM is uniquely able to image definable volumes beneath a surface. In Rugar and colleagues' experiment, 250 nm separates the tip and the resonant spin buried in the sample below. The large field gradient and the low spin density in the sample (of irradiated vitreous silica) ensure that individual spins can be selected.

This accomplishment also built on crucial advances in understanding and control of electron spin relaxation. The visibility of weak signals can be enhanced by coherently adding them together, because noise contributions, being random, will tend to add to zero. This improvement is limited by the lifetime of signal coherence, so long spin lifetimes are advantageous. However, bringing the micromagnetic tip close to the spins can reduce lifetimes by speeding relaxation[6]: thermal fluctuations of the cantilever move the micromagnetic tip randomly, so spins near the tip experience fluctuating magnetic fields; these fluctuations cause spins to relax[7]. Rugar *et al.* controlled this problem by fabricating a mass-loaded cantilever in which the problematic cantilever tip motions are suppressed[8].

MRFM is a unique single-spin detection technique, in that it couples directly to the electron's magnetic dipole moment. Other approaches exploit mechanisms that couple the spin of the electron to its spatial degrees of freedom, allowing detection through coupling to its charge (for instance, by monitoring an optical transition that is sensitive to the spin state[9,10]). Another approach rests on the Pauli exclusion principle, which sets symmetry constraints on the electron wave function (the mathematical description of its quantum state). As the electron wave function is a product of its spatial and spin components, the Pauli principle effectively couples spin and spatial degrees of freedom. Charge is much easier to detect than spin, but the better sensitivity afforded by these techniques — through charge detection, instead of spin detection — comes at the price that only in particular situations is it possible to arrange the required interaction between electron spin and orbital degrees of freedom.

In contrast, the MRFM approach is entirely general and can, in principle, be applied to the detection of any magnetic moment (nuclear[11] and ferromagnetic[12] MRFM have also been demonstrated). The 'in principle' qualification is a consequence of the difficulty of detecting an individual spin; this limits how rapidly measurements can be made. Further improving sensitivity could greatly enhance the range of applicability of MRFM. Higher spatial resolution will benefit fields from nanoelectronics to biomolecular imaging. As electronic elements become smaller, they become sensitive to the presence of individual impurities and dopants; hence three-dimensional atomic-scale characterization becomes crucial. Perhaps most notably, the field of spin-based quantum computation will require single-spin detection technology both for the readout of quantum states and for device characterization; single-spin MRFM promises to aid in this challenging undertaking. ■

P. Chris Hammel is in the Department of Physics, Ohio State University, Columbus, Ohio 43210, USA.

e-mail: hammel@mps.ohio-state.edu

1. Rugar, D., Budakian, R., Mamin, H. J. & Chui, B. W. *Nature* **430,** 329–332 (2004).
2. Wolf, S. A. *et al. Science* **294,** 1488–1495 (2001).
3. Sidles, J. A. *Appl. Phys. Lett.* **58,** 2854–2856 (1991).
4. Sidles, J. A. *et al. Rev. Mod. Phys.* **67,** 249–265 (1995).
5. Stowe, T. D. *et al. Appl. Phys. Lett.* **71,** 288–290 (1997).
6. Stipe, B. C., Mamin, H. J., Stowe, T. D., Kenny, T. W. & Rugar, D. *Phys. Rev. Lett.* **87,** 096801 (2001).
7. Mozyrsky, D., Martin, I., Pelekhov, D. & Hammel, P. C. *Appl. Phys. Lett.* **82,** 1278–1280 (2003).
8. Mamin, H. J., Budakian, R., Chui, B. W. & Rugar, D. *Phys. Rev. Lett.* **91,** 207604 (2003).
9. Wrachtrup, J., von Borczyskowskij, C., Bernard, J., Orritt, M. & Brown, R. *Nature* **363,** 244–245 (1993).
10. Kohler, J. *et al. Nature* **363,** 242–244 (1993).
11. Rugar, D. *et al. Science* **264,** 1560–1563 (1994).
12. Zhang, Z., Hammel, P. C. & Wigen, P. E. *Appl. Phys. Lett.* **68,** 2005–2007 (1996).

Embryology

Plane talk

Gerald Schatten and Peter Donovan

In mammals, is the three-dimensional body plan ingrained in the egg at or before fertilization? The answer is 'maybe, but then again maybe not'. Less invasive techniques might help to resolve matters.

Hans Spemann[1] neatly summed up the importance of embryonic axes for correct animal development: "We are standing and walking with parts of our body which could have been used for thinking had they developed in another part of the embryo." But how and when are the embryonic axes established? Elsewhere in this issue[2], Hiiragi and Solter (page 360) deliver the latest contribution to a debate over dividing embryos that is dividing embryologists.

Some unfertilized vertebrate and invertebrate eggs display undeniable polarity along a plane known as the animal–vegetal axis. The animal pole is defined by an area of meiotic cell division (whereby a nucleus divides into four, each resulting nucleus containing half of the original complement of chromosomes); by default, the opposite pole is vegetal. This axis is variously apparent from differences in surface smoothness and pigmentation, and features of the egg cytoplasm. But until recently such features had not been identified in mammalian eggs, raising the question of whether we mammals abandoned the instructions found in non-mammalian eggs for assembly of our body's three-dimensional plan.

Just a few years ago, groundbreaking work by Richard Gardner and collaborators[3,4], as well as Magdalena Zernika-Goetz and her group[5–7], provided compelling evidence that mouse eggs possess polarities that track closely with the later body planes. Perhaps in mammals, then, as in other animals, one or more of the three body planes (anterior–posterior, dorsal–ventral and left–right) are already ingrained in the egg before or during fertilization. From their studies with time-lapse video microscopy, however, Hiiragi and Solter[2] assert that the mouse egg does not display any predetermined axes.

During the maturation of an egg cell, it undergoes by meiosis a unique asymmetrical division into two cells: the secondary oocyte (which will become the egg) and the polar body. Further meiosis results in the asymmetrical division of the secondary oocyte into the mature egg and the second polar body, each containing a single set of chromosomes. Normal development results in the eventual degradation of the polar bodies, but while they persist they are often used as land-