show discernable and characteristic tunnel-current distributions for three of the four nucleotides, though the current distributions are much wider than those reported when functionalized electrodes are used. The Arizona State group also obtained broad distributions when bases were read with bare electrodes, but showed, through an analysis of the bound-state lifetimes, that the source of these distributions was most probably the well-known promiscuous binding of the imines and amines in bases to gold. The signal appears to be broadened by the large number of configurations that can bind a bare metal electrode, and not the free diffusion of bases, as was previously suggested[6].

Both these approaches are the first strides towards sequencing DNA using a physics-based technique that is label-free and capable of potentially obtaining sequence information at a very high rate. There are, however, many challenges to be overcome before these proof-of-principle experiments can be considered as a basis for a routine DNA sequencer. Even with functionalized electrodes, where distributions are quite narrow[7], there is some overlap of the signatures of the different nucleotides. Statistical techniques can resolve these signatures, but this costs time. Another challenge will be developing simple techniques for creating reliable and precise nanogaps. Other issues include localizing the nucleotide in the gap, controlling its speed, and thermal noise suppression. Furthermore, a practical challenge will be forcing the DNA to pass one base at a time through the tunnelling gap in a reproducible fashion, though the recent introduction of metallic carbon nanotubes as conducting nanopores for DNA control represents an important development in this direction[10].

Eventually, tunnelling in combination with nanopores could permit read lengths that approach a significant fraction of a whole genome. For practical applications this method should be adapted for DNA in buffered aqueous solutions. The methods reported by the Arizona State and Osaka groups partially answer many of these issues, and combining these approaches (as shown in Fig. 1) can potentially overcome some of the variations in the tunnel current signatures of the bases. Moreover, an improved understanding of the variables that contribute to the statistical spread of the currents will allow spatial and temporal control of bases in the gap, leading to rapid, single-shot experiments that can read DNA sequences for routine use. Just as similar challenges have been met before, these issues can be surmounted through the continuing development of a range of creative approaches. ❐

Thomas Thundat is at the Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA.
e-mail: thundattg@ornl.gov

References

1. www.ornl.gov/sci/techresources/Human_Genome/home.shtml
2. Schloss, J. *Nature Biotechnol.* **26,** 1113–1115 (2008).
3. Branton, D. *Nature Biotechnol.* **26,** 1146–1153 (2008).
4. Lee, J. W. & Thundat, T. US Patent 6,905,586 (2005).
5. Zikic, R. *Phys. Rev. E* **74,** 011919 (2006).
6. Zwolak, M. & Di Ventra, M. *Rev. Mod. Phys.* **80,** 141–165 (2008).
7. Chang, S. *et al. Nano Lett.* **10,** 1070–1075 (2010).
8. Tsutsui, M., Taniguchi, M., Yokota, K. & Kawai, T. *Nature Nanotech.* **5,** 286–290 (2010).
9. Meunier, V. *J. Chem. Phys.* **128,** 041103 (2008).
10. Liu, H. *et al. Science* **327,** 64–67 (2010).

SELF-HEALING MATERIALS

Get ready for repair-and-go

Computer simulations have shown that hydrophobic nanoparticles encapsulated in a deformable shell can repair surfaces in a manner that is similar to the way white blood cells work in the body.

Scott R. White and Philippe H. Geubelle

We are fortunate that our bodies are able to heal themselves with little or no intervention after a minor injury such as a small cut. This self-healing ability has inspired scientists to invent a range of different methods for restoring function to damaged materials[1]. However, there are many challenges to be overcome before self-healing materials are available for practical applications such as circuit boards and airplane wings[2]. Now, writing in *ACS Nano*, Anna Balazs and co-workers[3] at the University of Pittsburgh and the University of Massachusetts introduce a new concept in self-healing that is inspired by the ability of white blood cells to heal wounds in the body.

When the body is injured, certain molecules called mediators are released to help white blood cells find the site of the injury and activate a healing process[4]. Thus, white blood cells are recruited to the site of damage where they recognize the injured

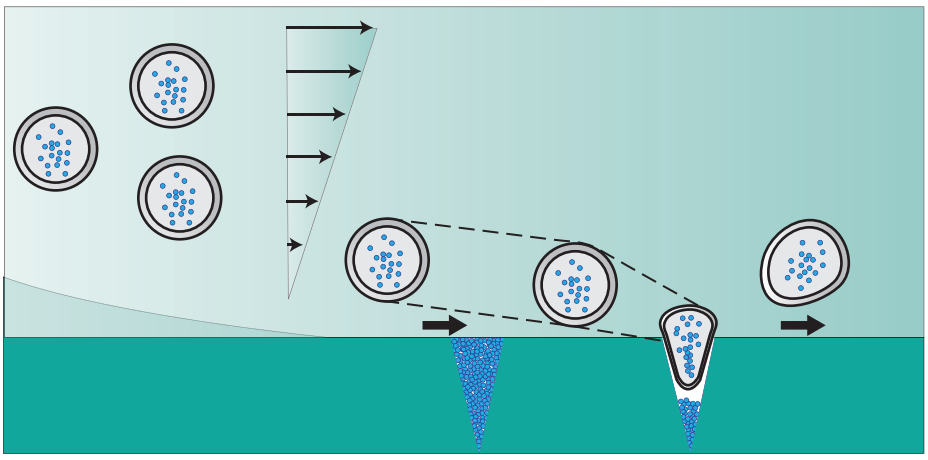

Figure 1 | The 'repair-and-go' approach to self-healing systems. Amphiphilic capsules (grey spheres) that contain hydrophobic nanoparticles (blue spheres) are released in a flow field. The capsules can recognize cracks, which have hydrophobic interiors, in the surface of the material (dark green), which is hydrophilic. Entropic forces cause the nanoparticles to be released into the crack. Once the crack has been repaired, or the flow conditions change, the capsules are released and go with the flow again.

© 2010 Macmillan Publishers Limited. All rights reserved

state and activate the repair process. Any synthetic self-healing system must mimic this regulatory feedback mechanism: the site of damage needs to recruit the components that are responsible for the healing, and once they are in the vicinity of the damage, these components must release and activate the repair agents.

This might seem like a tall order for inanimate synthetic components, such as organic polymers and nanoparticles, yet Balazs and co-workers have shown that properly designed capsules can demonstrate remarkable regulation of their behaviour. The basic premise is to disperse hydrophobic nanoparticles in oil and encapsulate them within a protective shell that is both deformable and amphiphilic (that is, it displays both hydrophobic and hydrophilic properties). The capsules are then dispersed in water. The Pittsburgh–Massachusetts team simulate a rigid hydrophilic surface that contains a crack, and assume that the interior of this crack is hydrophobic. Capsules that flow over the surface are attracted to the hydrophobic surface of the crack, and once they have been captured, entropy forces the nanoparticles out of the capsules and into the crack, ultimately leading to healing of the surface (Fig. 1).

Performing three-dimensional computer simulations based on the lattice Boltzmann model for the fluid dynamics and a lattice spring model for the deformable shells of the capsules, Balazs and co-workers examine the conditions necessary for the effective delivery of nanoparticles into the cracks. They show that capsules can be sequestered within the crack even in the presence of constant shear flow. This surprising result depends on both the attraction of the capsule to the hydrophobic crack and the deformability of the capsule shell. For strongly attractive capsules that deform easily, the capsule nestles within the crack and conforms to its surface, making it easier for the nanoparticles to fill the crack. This coupling between deformability and function is common in biological systems, where cell adhesion and spreading regulates processes such as cell migration and tissue formation[5].

The situation is even better for pulsatile flow regimes, when the flow switches between high and low shear rates. Capsules can be captured within a crack during low-shear-rate conditions, and then flushed out of the crack for high values of the shear rate. Thus, fluctuations in flow conditions can switch the repair function on and off. Capsules flushed out of a crack go with the flow again, until they are captured by another crack and the repair process is repeated. This continues until there are no longer any nanoparticles in the capsule.

The effectiveness of this 'repair-and-go' process is strongly affected by many factors including, among others, the geometry of the damage region, the interaction between the capsules and the flow, the delivery of the nanoparticles to the damage site, and the interactions between the capsules. Modelling these phenomena is particularly challenging given the lack of experiments in the field, but is also an exciting example of theory driving innovation and new ideas. Putting these ideas into practice will require experimentalists to develop capsules that are both robust and deformable, possess good adhesion characteristics, and able to release nanoparticles through their walls under appropriate conditions.

What is most exciting about the repair-and-go system simulated by Balazs and co-workers is that it seems to capture the essential nature of wound healing by white blood cells — a regulated delivery of healing components to specific sites of damage. Repair-and-go capsules could, for example, address the problem of capillary blockages in synthetic self-healing microvascular materials[6]. (These materials are repaired by healing agents that flow through a network of capillaries inside the material). Just as with the human arterial system, blockages can form within self-healing microvascular materials when the repair process proceeds too far, too fast or without regulation. Capsules such as those described by Balazs and co-workers could be transported within the vascular network, captured at the site of damage, and then flushed downstream after the healing process is complete.

These latest developments in self-healing concepts point towards future repair mechanisms that use simple principles — such as tuning the hydrophobicity of surfaces — to achieve high levels of control and regulation. Other surface interactions could also be used to target specific types of damage or specific materials needing repair in multicomponent systems. Eventually, when specific molecular units are grafted onto the capsules to improve the recognition capabilities even further, the self-healing equivalent of the highly targeted enzyme/substrate or antibody/antigen pairings found in nature will be complete. ❐

Scott R. White and Philippe H. Geubelle are in the Department of Aerospace Engineering and the Beckman Institute of Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA.
e-mail: swhite@illinois.edu

References

1. Caruso, M. M. *et al. Chem. Rev.* **109,** 5755–5798 (2009).
2. Patel, P. *MIT Technology Review* 22 (Sept–Oct 2007).
3. Kolmakov, G. V. *et al. ACS Nano* **4,** 1115–1123 (2010).
4. Schaffer, M. & Barbul, A. *Brit. J. Surgery* **85,** 444–460 (1998).
5. Friedl, P. & Wolf, K. *J. Cell Bio.* **188,** 11–19 (2009).
6. Toohey, K. S. *et al. Adv. Funct. Mat.* **19,** 1399–1405 (2009).

WATER DESALINATION

Fresh for less

Salt water can be separated into desalted and saltier streams by a nanochannel-based device that requires only low-voltage electricity.

Mark A. Shannon

The number of different ways that humans have found to get fresh water from salt water is testament to our inventiveness. In 1589, for example, Della Porta chronicled seven ways to distil water, which included a solar desalinator of brackish water[1]. Today numerous methods are available[2]: electrically driven electrodialysis and capacitive separations; thermally driven methods using flash and multi-effect distillation, vapour compression and forward osmosis; pressure-driven reverse-osmosis membrane desalination, which was developed in the 1950s and 1960s and now dominates newly

© 2010 Macmillan Publishers Limited. All rights reserved