

phase-flip errors, simultaneously, and in a scalable architecture<sup>10,11</sup>. The remaining obstacles should not be underestimated. Individual quantum logic fidelities need to be improved to a regime comfortably beyond the fidelity threshold. This is both a challenge in materials for improving qubit coherence times, as well as in device design. An architecture must be developed that allows for the wiring and control of two-dimensional arrays of qubits, which permits eventual scaling up to thousands or millions of them. Systems that are compatible with controlling and processing data from these large qubit systems must

be invented. All these are engineering problems, albeit of a fiercely demanding kind; there do not seem to be any fundamental physical barriers remaining to thwart our progress. Perhaps Feynman's wonderful problem, which has stimulated so much beautiful and far-reaching quantum science, will soon be recognized as solved. Then at last we may realize his dream, which so many others now share: to fully harness the computational power of the quantum world. □

Simon Benjamin is in the Department of Materials, University of Oxford, 16 Parks Road,

Oxford OX1 3PH, UK. Julian Kelly is at Google, Santa Barbara, California 93106, USA. e-mail: [simon.benjamin@materials.ox.ac.uk](mailto:simon.benjamin@materials.ox.ac.uk); [juliankelly@google.com](mailto:juliankelly@google.com)

#### References

1. <http://www.cs.berkeley.edu/~christos/classics/Feynman.pdf>
2. Ristè, D. *et al. Nature Commun.* **6**, 6983 (2015).
3. Córcoles, A. D. *et al. Nature Commun.* **6**, 6979 (2015).
4. Bassett, L. C. *et al. Science* **345**, 1333–1337 (2014).
5. Harty, T. P. *et al. Phys. Rev. Lett.* **113**, 220501 (2014).
6. Ballance, C. J. *et al. Preprint at* <http://arXiv.org/abs/1406.5473v1> (2014).
7. Barends, R. *et al. Nature* **508**, 500–503 (2014).
8. Nigg, D. *et al. Science* **345**, 302–305 (2014).
9. Kelly, J. *et al. Nature* **519**, 66–69 (2015).
10. Fowler, A. J. *et al. Phys. Rev. A* **86**, 032324 (2012).
11. Nickerson, N. H. *et al. Phys. Rev. X* **4**, 041041 (2014).

## PUSHING NANOTUBES TO THE LIMIT

It is a little shocking to realize that researchers have been trying to separate carbon nanotubes for over two decades. It soon became apparent after the first synthesis of single-walled nanotubes (SWNTs) in 1993 that their electrical properties depend on the precise atomic structure of the walls, specifically on the direction about which the graphene sheet is rolled to make a cylinder. This structure can be characterized by a pair of integers  $n, m$  that define the tube diameter and the helicity of the conjoined hexagons winding chirally along the tube axis. Tubes for which  $n = m$  are metallic, the others are semiconducting.

This dual nature accounts both for the initial promise in using SWNTs for nanoelectronics (you can use them for both conducting and semiconducting components) and part of the difficulty of realizing it: synthetic methods offer little control over the  $n, m$  indices, so you need to separate the two types. While the differences between electronic and semiconducting properties are sufficient to enable this crude separation with reasonable efficiency<sup>1</sup>, some applications<sup>2</sup> need a more fine-grained sorting so that all the nanotubes in a single sample have the same chirality — that is, identical  $n, m$ .

While the problem hardly rivals the importance of isotope separation in the Manhattan Project, or of DNA fragments in genetic analysis and sequencing, it raises similar issues of how tiny differences in physical or chemical properties can

be exploited for purification. Some of the standard techniques used in both of those previous separation problems, such as centrifugation and gel chromatography, have been adapted to SWNTs. For example, chirality-dependent differences in the interaction strengths of nanotubes with a dextran gel are adequate to enable their progressive separation by chromatography<sup>3</sup>, while analogous differential interactions with DNA or surfactants can be exploited in density-gradient centrifuge techniques<sup>4,5</sup>.

Yet not only are such chemical methods still a little messy, but it would be nice to conduct a separation based on first-principles selection of a particular nanotube structure rather than by empirical calibration. Building on earlier work showing preferential optical trapping of SWNTs of specific chirality in optical tweezers<sup>6</sup>, Skelton Spesyvtseva *et al.* have now shown that nanotubes can be optically sorted by using a Raman scattering resonance of the bandgap energy to enhance the optical force experienced by a specific  $n, m$  nanotube<sup>7</sup>.

In short, a laser beam shone along the axis of a capillary containing a mixed suspension of SWNTs pushes one type of tube chirality selectively towards the far end, as revealed by the Raman spectra of that region. While the 'pushing' wavelength is slightly longer than the Raman excitation wavelength of the SWNT in question, this offset is explained by scattering theory. □



PHILIP BALL

The enrichment achieved this way is so far merely qualitative and will not alone lead to total purification. But finer separation efficiency might be attained by, for example, using a counter-propagating beam to propel the other nanotubes in the opposite direction. And using circularly polarized light, it might even be possible to separate tubes that differ only in their handedness.

The ultimate ideal is selective synthesis of SWNT chirality in the first place. But that remains a major challenge<sup>8</sup>. □

#### References

1. Krupke, R., Hennrich, F., v. Löhneysen, H. & Kappes, M. M. *Science* **301**, 344–347 (2003).
2. Baughman, R. H., Zakhidov, A. A. & de Heer, W. A. *Science* **297**, 787–792 (2002).
3. Liu, H., Nishide, D., Tanaka, T. & Kataura, H. *Nature Commun.* **2**, 309 (2011).
4. Arnold, M. S., Stupp, S. I. & Hersam, M. C. *Nano Lett.* **5**, 713–718 (2005).
5. Arnold, M. S., Green, A. A., Hulvat, J. F., Stupp, S. I. & Hersam, M. C. *Nature Nanotech.* **1**, 60–65 (2006).
6. Rodgers, T., Shoji, S., Sekkat, Z. & Kawata, S. *Phys. Rev. Lett.* **101**, 127402 (2008).
7. Skelton Spesyvtseva, S. E., Shoji, S. & Kawata, S. *Phys. Rev. Appl.* **3**, 044003 (2015).
8. Wang, H. *et al. Carbon* **81**, 1–19 (2015).