Only all of the harmonics together can provide a spatial image. But different harmonics are generated at different times, and the shape of the hole is changing: the relative phase between the two states changes by about π/2 between the 17th and 31st harmonics[3]. Thus, only for one harmonic do the contributions from the two participating states coincide with real and imaginary parts of the measured dipole. As a result, there is an inevitable trade-off between temporal resolution and accuracy in separating the contributions of the two orbitals, and the image is inevitably distorted — not just blurred. The experiment[3] yields a single image, taken with 600 as exposure, of the 1.5-fs hole motion from one side of a molecule to another.

How is it possible to deal with the trade-off between space and time? One can focus on the time-domain information encoded in high harmonics while using theory for spatial information[8,10]. But is it possible to do better? To what extent can both space and time information be extracted from the same measurement? What if more than two orbitals are present? To what extent does the orbital, recognizable only by the nodal plane imposed during reconstruction[3], represent HOMO-1? Did the strong laser field affect the motion of the hole? Addressing these questions is an exciting prospect — and possibly ground for more controversy ahead. ❐

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References

1. Breidbach, J. & Cederbaum, L. S. *Phys. Rev. Lett.* **94,** 033901 (2005).
2. Hennig, H., Breidbach, J. & Cederbaum, L. S. *J. Phys. Chem. A* **109,** 409–414 (2005).
3. Haessler, S. *et al. Nature Phys.* **6,** 200–206 (2010).
4. Itatani, J. *et al. Nature* **432,** 867–871 (2004).
5. Schwarz, W. H. E. *Angew. Chem. Int. Ed.* **45,** 1508–1517 (2006).
6. Walters, Z. B., Tonzani, S. & Greene, C. H. *J. Phys. Chem.* **112,** 9439–9447 (2008).
7. Lein, M. *J. Phys. B* **40,** R135–R173 (2007).
8. Baker, S. *et al. Science* **312,** 424–427 (2006).
9. Smirnova, O. *et al. Phys. Rev. Lett.* **102,** 063601 (2009).
10. Smirnova, O. *et al. Nature* **460,** 972–977 (2009).

QUANTUM MECHANICS

Intellectually delicious

It is 50 years since the discovery of the Aharonov–Bohm effect, and 25 years since that of the Berry phase. A celebration of this double anniversary at the University of Bristol made evident that these discoveries still offer much food for thought.

Murray Peshkin and Lev Vaidman

The meeting celebrating the fiftieth anniversary of the Aharonov–Bohm effect and the twenty-fifth anniversary of the Berry phase was held on 14–15 December 2009 in the historic H. H. Wills Physics Laboratory of the University of Bristol, UK. That time and place provided the perfect atmosphere for the purpose. The university was celebrating its own one-hundredth anniversary, and the physics laboratory had been home to the two discoveries being celebrated, each of which changed the way we think about a fundamental concept in physics. It was also home to Robert Chambers's first experimental demonstration of the Aharonov–Bohm effect, using electron interferometry. And it remains the leading centre of the study of geometric phases and the scientific home of Michael Berry and of Sandu Popescu, who chaired the organizing committee for the meeting.

When Yakir Aharonov and David Bohm discovered in 1959 that the quantum-mechanical motion of a charged particle can depend on electric and magnetic fields confined to regions from which the particle is rigorously excluded, they were greeted by widespread surprise and disbelief. Today we know from experiment that the effect is unarguably real, and it is now widely understood to imply that — contrary to what was almost universally believed on the basis of classical physics — the motion of a particle is not always determined by the local Maxwell fields alone: the vector and scalar potentials are unavoidably carriers of physical information. The Aharonov–Bohm effect has since been extended to non-Abelian gauge theories, and it has become a useful tool in experiments that investigate properties of condensed matter.

Michael Berry's discovery of the pervasive geometric phase in 1983 (his seminal paper was published in 1984) was a different kind of surprise. It unified phenomena as diverse as the classic Foucault pendulum and the Born–Oppenheimer approximation in the quantum mechanics of molecules, by reducing them to geometry and enabling the geometrical phases to be calculated independently of many specifics of the problem at hand. It is reminiscent of the impact of the introduction of group theory in the early days of quantum mechanics. No problem could be solved with it that could not be solved without it, but the insight gained and the ease of calculation that rewarded the geometric approach had a major impact on what could be and was done.

The importance of those two achievements, which are not entirely unrelated to each other in the physics they revealed, was recognized in 1998 when Aharonov and Berry shared the Wolf Prize in Physics. However, the two honourees approach physics from radically different directions. Aharonov typically challenges our fundamental assumptions through very basic logic. (He good-naturedly denied at the meeting in Bristol that he never calculates anything.) Berry typically approaches problems through sophisticated mathematics, revealing remarkable generalizations.

At the anniversary celebration, Chambers and Anthony Klein told mostly, but not exclusively, of things that do not appear in journal articles: difficulties overcome and the human interactions in their early experiments. Akira Tonomura described a new proposal for three-dimensional electron holography and Naoto Nagaosa discussed the use of the Berry phase and topology in condensed-matter physics. Three very entertaining applications of geometric phases were Andre Geim's levitation of frogs in a strong magnetic field, Ulf Leonhardt's bending of light to make objects invisible, and Joseph Avron's explanation of how to lift yourself out of a swamp by your bootstraps (if you happen to live in a curved space). As part of the university's centennial celebration, Fields medallist Michael Atiyah gave a public lecture on topology and quantum mechanics. To do

WOLF FOUNDATION

Michael Berry (standing) and Yakir Aharonov during the 1998 Wolf Prize awarding ceremony in the Chagall hall of the Israeli *Knesset*.

that would seem to be a daunting challenge, but he did connect successfully with a general audience.

The two keynote talks were given by the celebrants. Berry spoke of the interplay between the Aharonov–Bohm effect and the geometric phase in the motion of magnetic half-fluxons in a cloud of electric charges. Aharonov and co-workers had analysed such a problem in the past through qualitative insights. Berry's mathematics allowed him to discover remarkable new features, which he named the 'dance of degeneracies' after the intriguing motions of the topological singularities in the wave functions.

The last talk, by Aharonov, had an unusual format for such a meeting. He presented his ideas about measurement in quantum mechanics by challenging the audience with a paradox involving apparent non-conservation of momentum and inviting discussion. Berry picked up the mathematical subtlety of the paradox and a lively discussion ensued with the audience refusing to leave until the session was extended for half an hour. Aharonov's resolution of the paradox was complete uncertainty of the modular momentum. In his interpretation, the indeterminacies of quantum mechanics are in fact necessary to preserve causality in the measurement process.

The paradoxes, physical and mathematical insights, and experimental achievements reported at the meeting were perhaps best described in the words of Michael Berry, who called the meeting "intellectually delicious".❒

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NEURAL CONTROL

Chaos control sets the pace

Even simple creatures, such as cockroaches, are capable of complex responses to changes in their environment. But robots usually require complicated dedicated control circuits to perform just a single action. Chaos control theory could allow simpler control strategies to realize more complex behaviour.

Eckehard Schöll

Chaos is usually associated with undesirable disorder. In mathematics, chaos is the behaviour shown by any nonlinear dynamic system whose time evolution depends sensitively on its initial conditions, rendering prediction of its future state practically impossible even though it is strictly deterministic. And so it would seem counterintuitive to use chaos to generate well-structured ordered behaviour as needed in robotic control. Yet, writing in *Nature Physics*[1], that is essentially what Steingrube and colleagues describe, in a report that shows that a relatively simple control algorithm based on chaotic behaviour can permit a hexapod (six-legged) robot to exhibit a complex array of adaptive behaviours that allow it to successfully navigate its way through a disordered and changing environment.

A key concept in chaos theory is that of a chaotic attractor. The building blocks of a chaotic attractor (such as the Rössler attractor represented in Fig. 1a) in a system's phase space are formed by many unstable periodic orbits of different periods. The time trajectories wander erratically between these different unstable solutions, which gives an intuitive picture of chaotic motion. At the same time this opens the possibility of generating different kinds of ordered behaviour from chaos by stabilizing any one of these unstable periodic orbits by a small self-adaptable control force, which perturbs the neighbourhood of those unstable orbits such that they become attractive, that is, stable, and without changing the orbits themselves. This is the essence of chaos control.

One of the simplest implementations of chaos control uses time-delayed feedback. This involves a control signal, $u(t)$, that is proportional to the difference in the value of some output variable, $y(t)$, at the present time, t, and some time, $t-p$, in the past, where p is the delay time. That is, $u(t) = K(y(t)-y(t-p))$, where K is a coefficient that determines the feedback strength (see Fig. 1a). Choosing the value of p, so that it is the same as the period of some desired unstable periodic state, one can stabilize this state for suitable values