placental mammal with four molars); six extinct species (some as old as 55 million years); and species in which the first molar is much smaller than the second, which is in turn much smaller than the third (M1<<M2<<M3). All of these extreme phenotypes fall within the areas of morphospace consistent with Kavanagh and colleagues' model (the white areas of Fig. 3). Furthermore, plant-eating species tend to be in the high-*a*/*i* region, where M1<M2<M3 (upper white area), and animal-eating species tend to be in the low-*a*/*i* region, where M1>M2>M3 (lower white area), paralleling the pattern that Kavanagh and colleagues found in rodent species.

Areas of morphospace that are not consistent with their model are sparsely occupied (see the coloured areas in Fig. 3). Three species of bear fall deep in the region where M1<M2>M3, a pattern that Kavanagh *et al.* say requires early arrest of M3 development in addition to a decrease in inhibition. The horse falls (marginally) into the region where M1>M2<M3, which Kavanagh *et al.* say is the developmentally least likely phenotype. Members of the raccoon family, which have only two molars, are also an exception because their M2 is more than half the size of M1, larger than expected for animals that have lost M3.

Few developmental models derived from a single species are able to predict quantitative phenotypic variation across such huge evolutionary distances with such accuracy as does Kavanagh and colleagues' model. But tests need not end here. The model allows *a*/*i* to be estimated from the dental phenotypes of both extant and extinct species, and to be tested in the lab for extant species. The study of signalling in raccoons or bears should reveal an interesting pattern of tooth-bud activation, inhibition and growth that deviates from Kavanagh and colleagues' findings in mice. ■

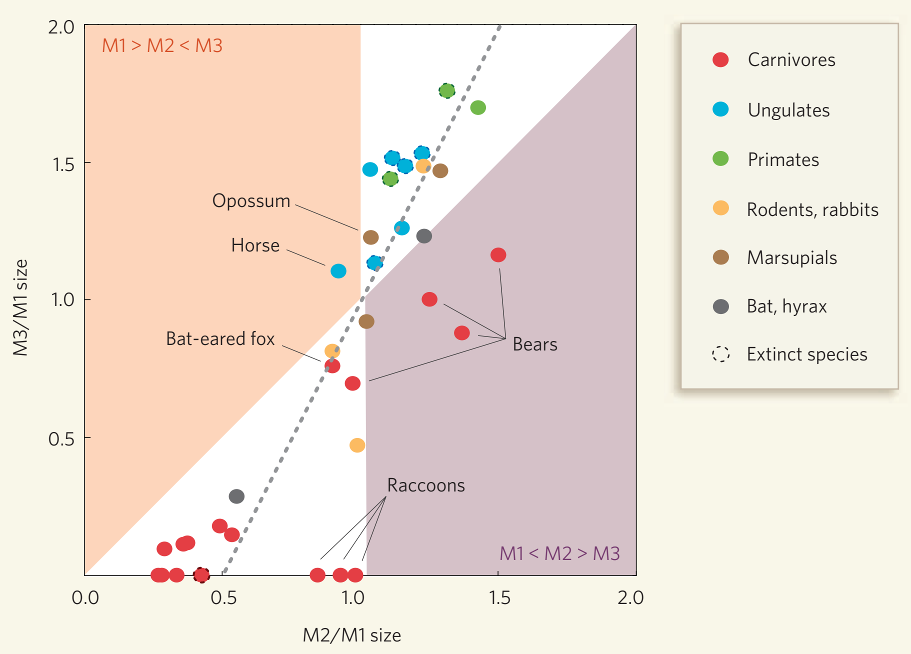

Figure 3 | Molar proportions in developmental 'morphospace'. Data from 35 species, compiled from my own measurements of specimens in the Indiana University Zooarchaeology Laboratory, show that Kavanagh and colleagues' model can largely account for patterns of molar-size proportions in mammals. The white region is consistent with their model; the broken line is the relationship they predicted. The bat-eared fox and opossum fit the model despite having four molars. Three species of bear do not fit the model (in that early arrest of M3 development is required in addition to a change in *a*/*i*); nor does the horse (though there is no obvious explanation for this). The raccoons have a proportionally larger M2 than expected for species without an M3.

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QUANTUM PHYSICS

Qubits ride the photon bus

Antti O. Niskanen and Yasunobu Nakamura

Quantum mechanics using whole electrical circuits might seem a far-fetched idea. But make the circuits superconducting, and they can be used to send and collect single photons, rather like atoms do — only better.

The interaction of light and matter is all around us: we can see the objects that surround us only because their constituent atoms continuously emit and absorb electromagnetic radiation. Not only visible light, but everything from γ-rays through to radio waves, and even the alternating fields of power lines and the gigahertz signals inside a digital computer, are manifestations of fundamentally the same thing at different energy scales — the propagation of the discrete packets of electromagnetic energy known as photons.

In most situations, the presence or absence of a single photon does not make a noticeable difference to what happens. But this is not so in the nascent field of quantum computing, and that explains the significance of two papers in this issue, by Sillanpää *et al.* (page 438)[1] and Majer *et al.* (page 443)[2]. These authors describe experiments in which single photons transfer quantum information between relatively distant quantum bits (qubits) in a nanofabricated circuit held at a low temperature, so that the circuit loses its electrical resistance. Taken together with a closely related paper by Houck *et al.* in last week's issue[3], which recounted how such superconducting circuits can be used to produce single photons on a chip, these papers represent confident steps towards the ultimate goal of a viable, large-scale quantum computer. But they also stand on their own as wonderful examples of how science can mimic the ubiquitous natural interactions between atoms and light.

In principle, a serviceable quantum computer needs a collection of fully controllable qubits. A qubit can be represented by pretty much anything physical that can form a system of two states (representing 0 and 1) and behaves according to quantum theory. In practice, this means that the system must be as completely isolated from everything as possible. The most obvious choice for a qubit is one of nature's own-brand offerings — be they ions, atoms, molecules, electrons or photons. These microscopic objects can often be well isolated from their surroundings, but are quite difficult to control.

Despite their macroscopic size, specially designed electrical circuits provide a promising alternative basis for a quantum computer: their parameters can be adjusted, individual controls and measurements are relatively simple, and the system size can be scaled up. An essential ingredient for quantum computers is the ability to control the interactions between individual qubits for a 'universal entangling operation' to intertwine their quantum states. Qubits should be able to couple strongly, but they should also

GENOMICS

Vine work

The draft genome sequence of *Vitis vinifera*, the grapevine, described in this issue, provides plenty of scope for discussion over a glass of its fermented product. The sequence was published online on 26 August and now appears in print (The French–Italian Public Consortium for Grapevine Genome Characterization *Nature* **449,** 463–467; 2007).

The grape variety concerned is Pinot Noir, the classic red grape of Burgundy. But the vine sequenced does not produce exactly the same grape as that grown in the vineyards. The consortium chose to sequence a variety called PN40024, which has been bred by successive self-crossings to reduce the high degree of sequence variation that is characteristic of all grapevine varieties. The inbred strain allows efficient assembly of a high-quality sequence from whole-genome shotgun sequence data. In the shotgun technique the DNA is broken into many small fragments for sequencing and then reassembled from overlapping sequences.

The resulting genome sequence carries the imprint of millennia of selective breeding. For example, there are 116 genes and pseudogenes for terpene synthases, almost three times the number in the other three plant genomes so far sequenced. These enzymes synthesize the terpenoids that contribute to the aroma and flavour of wines, and pathways associated with tannins are similarly amplified.

Less obviously a target of selectivity are the genes that control the synthesis of resveratrol, the antioxidant credited with the health benefits claimed for moderate consumption of red wine. Yet there is a modest expansion, compared with the other sequenced plants, of the stilbene synthase genes associated with resveratrol synthesis.

So can we look forward to genetically engineered 'designer' wines? Probably not. There is a market for new grapes, as exemplified by Cabernet Sauvignon clone 337, which is gaining ground in California's Napa Valley. But the flavour and aroma of wine depend on many other factors, such as growth conditions and production methods. And when it comes to producing wines with greater health-giving properties, the prospect sounds too good to be true. So it probably is. However, grapevines are notoriously susceptible to pathogens and stresses, such as drought, that other *Vinus* species can resist. The availability of this genome sequence should speed up progress on introducing the appropriate resistance into economically important varieties of *V. vinifera*.

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With one grapevine genome sequenced, the way is clear for comparative oenogenomics. Yet when it comes to taste, perhaps the differences between a Pinot Noir with earthy and berry notes and a spicy or blowsy Gewürztraminer are best left to the realms of individual taste and a good thesaurus.

Charles Wenz

efficiently decouple. This is where the new work comes in[1–3], as it demonstrates how an on-chip photon field can act as a 'bus', or conduit, for quantum information, thus allowing a pair of distant qubits to interact at will.

Sillanpää and colleagues' qubits[1] are carefully designed, micrometre-sized elements of a superconducting circuit. These elements are coupled to opposite ends of an on-chip electrical resonator, or 'cavity', in which a standing electromagnetic wave of several millimetres' wavelength is established. Using an external source of microwave light, the authors first prepared one of their qubits in a superposition of its ground and first excited energy states. They then transferred this state to the photon field in the adjacent cavity — the bus. Finally, at the other end of the bus, they mapped the state of the photon field to the state of another qubit initially in its ground state. A further universal entangling operation between qubits could be achieved with extra tricks involving 'visits' to either higher qubit energy levels or larger numbers of photons. Such tricks are often applied in similar experiments in systems that use trapped-ion vibrations, rather than photons, as the bus medium[4,5].

Majer and colleagues' work[2] is similar, but comes with an additional twist. They also can carry out quantum-state transfer over a large distance, but in their case they never actually excite the intermediate photon field. Instead, they use 'virtual' photons, which are very weak perturbations of their cavity's quantum light field. This sleight-of-hand allows the authors to carry out a universal entangling operation on a pair of distant qubits, without disturbing the bus itself.

Houck *et al.*[3] performed complementary work by demonstrating a 'single-photon gun' that generates forwards-flying photons, instead of photons confined in a cavity, that have a well-defined phase of oscillation. They did this by first preparing an arbitrary quantum state in a superconducting qubit tightly coupled to a cavity. They then allowed the qubit to decay spontaneously, so that it emitted a single photon into a transmission line for microwave light. Convincing data from quantum-state tomography of both the qubit and the photon show how the qubit's initial state is transferred to the photon.

A great advantage of recent circuit architectures that exploit such 'cavity quantum electrodynamic' (cavity QED) approaches[6–8] has been that the interaction between a superconducting qubit and a cavity can be much larger than the equivalent coupling between a real atom and a cavity. In addition, there is in principle room for hundreds of qubits on the same chip. Because any pair of qubits can be coupled, implementing algorithms and error-correction codes[9] in a quantum computer will be significantly easier. One can also speculate that flying qubits such as those demonstrated by Houck *et al.*[3] could be used to communicate between chips for a further scaling up.

But once qubits have been coupled using a photon field as a bus, how well can they be decoupled? One way to do this would be to ensure that the qubit excitation frequency is different from the resonance frequency of the cavity. This can help to suppress the coupling between the qubits and the cavity, but might not be enough for long timescales and for many qubits. A possible future direction would be to combine the best features of cavity-bus architectures and 'nonlinear parametric couplers'[10], which provide both tunable coupling and better isolation in their 'off' state.

A big remaining unknown is whether the lifetimes of complicated multi-qubit states can be made long enough for practical quantum computing. Nevertheless, the latest experiments[1–3] on cavity–qubit interactions add significantly to the already large body of evidence showing that even relatively macroscopic objects can behave purely according to the laws of quantum physics — with all the promise that that holds for large-scale applications. ■

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