variation in flowering time. The effects of all QTLs were, however, small. Tests for epistasis and genotype-environment interactions revealed very little contribution of context-dependent effects to the genetic architecture of flowering time.

Using the NAM population for high-resolution recombination mapping will not be possible until the parent strains are genotyped for a dense panel of molecular markers. The large numbers of QTLs, small effects, and likelihood of identifying novel genes affecting quantitative traits from dissection of natural genetic variation pose a challenge for functional validation.

The observation of large numbers of QTLs with small effects on flowering time is consistent with results from mice, flies (*Drosophila melanogaster*), and humans for many different quantitative traits (*5*). However, the lack of QTLs with large effects is in contrast to the genetic architecture of flowering time in rice, barley, sorghum, and the model flowering plant *Arabidopsis thaliana*, where large-effect QTLs account for most of the observed variance (*6–9*). The trivial contribution of epistasis is also in contrast to epistatic interactions affecting flowering time in *Arabidopsis* (*10*) and rice (*11*), as well as the common occurrence of epistasis affecting quantitative traits in *Drosophila* and mice (*5*). Genotype-environment interaction is also a typical feature of the genetic architecture of quantitative traits in *Drosophila* and mice (*5*). The extent to which mating system, demography, sampling, experimental design, and relationship to fitness contribute to the genetic architecture of quantitative traits is an open question.

Genetic variation for most quantitative traits in most organisms may well be attributable to large numbers of loci with small effects. What, then, is the future of genetic dissection of complex traits? Rather than analyzing one gene at a time, we will need to understand how molecular variants affect quantitative traits through correlated networks of transcripts, proteins, and metabolites. The NAM population joins the mouse Collaborative Cross (*12*), the *Drosophila* Genetic Reference Panel (*13*), and the *Arabidopsis* 1001 Genomes Project (*14*) projects as a community resource population suitable for such systems' genetics analysis (*15*, *16*).

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PHYSICS

Quantum Football

Franco Nori

A superconducting circuit passes a quantum state between several energy levels like a football is passed between players.

Quantum information processing is usually based on two-level quantum systems, called quantum bits or qubits, but the use of additional quantum levels can simplify some quantum computations. It can also allow the emulation of other quantum systems, in which one quantum system acts as an analog of another and allows it to be better understood by reproducing its dynamics in a more controllable manner. On page 722 of this issue, Neeley *et al.* (*1*) demonstrate the operation of a superconducting circuit with five quantum levels, and show how to manipulate and measure its quantum states. They used this circuit to emulate the dynamics of single spins with various quantum numbers, including the measurement of their geometric phases that result from spin rotations. This extension of the two-level qubit to a multilevel "qudit" opens possibilities for richer quantum computing architectures and better emulations of other quantum systems.

Superconducting circuits can behave like atoms, in that both systems have discrete energy levels, and coherent quantum oscillations can occur between those levels. Such circuits can perform microscopic quantum mechanics at macroscopic scales and can be used to conduct atomic-physics experiments on a silicon chip (*2–4*). However, whereas transitions between electronic energy levels in atoms are controlled with visible or microwave photons, transitions in the artificial atoms are driven by currents, voltages, and microwave photons.

Quantum circuits can be lithographically designed to have specific characteristics, such as a large dipole moment (*2–5*) or particular transition frequencies. This tunability is an important advantage over natural atoms for several applications. For example, quantum circuits can produce photons (*6–8*), can be cooled (*9–11*) like natural atoms, can form molecules (*12*), and can be used for quantum memories (*13*, *14*).

For applications in quantum computing, quantum circuits have been designed to store and manipulate information as two-level quantum systems, called qubits (*2*, *3*). The greater complexity and flexibility of a many-level quantum system can be illustrated by making analogies with a classical system, that of a game of football (soccer). The main characters in standard quantum information processing are two players (two energy levels that form a qubit) with player numbers $|0\rangle$ and $|1\rangle$. The state of the quantum system—the football—can be written as the sum of $a{\cdot}|0\rangle + b{\cdot}|1\rangle$, where a and b are complex numbers that can vary in time but always satisfy the normalization condition $|a|^2 + |b|^2 = 1$. For instance, when ball state = $|0\rangle$, the ball is with player $|0\rangle$. In general, the quantum ball is in a superposition state: It is shared between both players.

Now, consider quantum information with several states. In the experiment by Neeley *et al.*, the states in their quantum circuits can emulate a particle with spin s, which can be described as a vector rotating on a sphere. When a spin rotates as it moves around a closed path, the spin state that describes it is multiplied by a phase factor, often referred to as Berry's phase. This phase factor depends on the solid angle enclosed by the path. For a 2π rotation, integer spins are unchanged, whereas half-integer spins are multiplied by –1. This parity difference leads to the symmetric statistics

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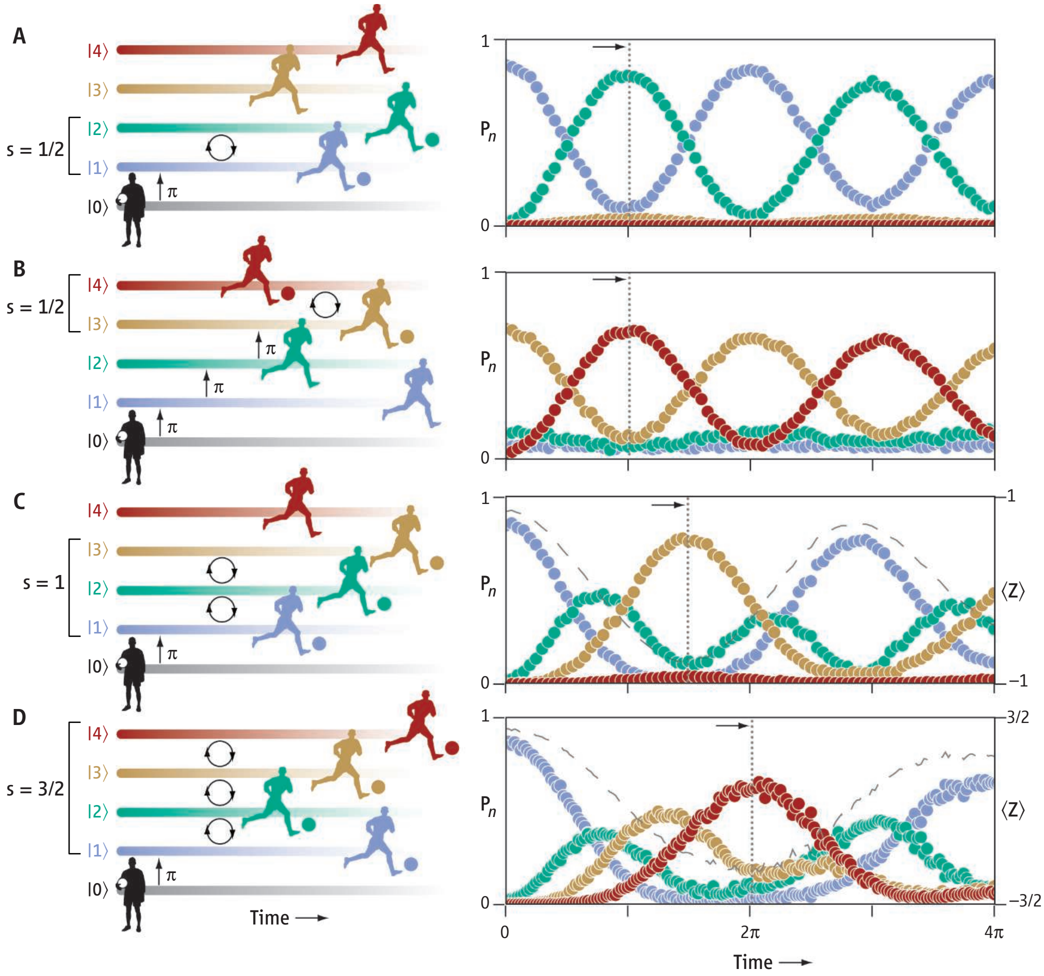

All players have some of the ball. In quantum football, this statement is literally true, because the occupied state, or quantum football, is probabilistic in nature—it can be at more than one place at any given time. The left side of each panel shows the sequences of operations that transfers the occupied state between five discrete energy levels of an artificial atom based on superconducting circuits. Each state $|n\rangle$ can be thought of as a player in football. On the right side, the occupancy of the energy levels as a function of time is expressed as a probability P_n, which corresponds to having the ball. Transitions between levels correspond to passes between players. The $|0\rangle$ state serves as a reference; in the football analogy, it is the goalkeeper. (**A**) Player $|0\rangle$, the goalkeeper, passes the ball to a defender, player $|1\rangle$; this pass is called "π shift" because it corresponds to a π rotation of the ball's quantum state. Afterward, defenders $|1\rangle$ and $|2\rangle$ repeatedly pass the ball to each other; these passes correspond to Rabi oscillations (shown as a black circle) and emulate a spin-1/2 system. The probability that other players have the ball is almost zero. (**B**) A series of π shifts gets the ball to the midfielders, $|3\rangle$ and $|4\rangle$, who repeatedly pass the ball to each other. The probability of player $|4\rangle$ controlling the ball at time π is lower than that for player $|2\rangle$ at the same time in (A). (**C**) A quantum ball repeatedly passed among three players can simulate a spin-1 system. (**D**) Repeatedly passing the ball among four players can simulate a spin-3/2 system. In (C) and (D), the circuit drives multiple transitions simultaneously to emulate spin operators. The expectation value $\langle Z\rangle$ that sums over all of these probabilities (far right) evolves sinusoidally (gray dashed curve), as expected for a rotating spin. The vertical dotted lines in the four right-side panels indicate the times when one of the players is more likely to have the ball.

of bosons and antisymmetric statistics of fermions under particle exchange.

Neeley *et al*. measured the phase factor and spin parity for spin-1/2, spin-1, and spin-3/2, at all solid angles, using their superconducting circuit as a quantum simulator. Their circuit reproduced the quantum phase acquired by each spin under closed-path rotations, in particular the even parity of integer spins and odd parity of half-integer spins under 2π rotation. This demonstration opens possibilities for using qudits in quantum information processing.

In the football analogy, the ball, which represents the occupied state, can be shared between many energy levels (players). Microwave pulses drive transitions between levels. For example, a π shift transfers the state completely, as happens when the goalkeeper $|0\rangle$ throws the ball to his defender $|1\rangle$ (see the figure, panel A). It is also possible to induce Rabi oscillations that allow the occupied state to oscillate between two energy levels and emulate a spin-1/2 state; this would correspond to two players passing the ball between them as they head upfield (see the figure, panels A and B). Adding more Rabi oscillations emulates higher spin states, corresponding to three or four players sharing the quantum football (see the figure, panels C and D). Unlike ordinary football, the quantum football has a probabilistic nature, so at no time can we be sure who has the ball.

Future directions and extensions of this work include developing qudit tomography, which would provide snapshots of the quantum states, as well as understanding decoherence in qudits and controlling the coupling and entangling of qudits. Applications of qudits include enhanced quantum memory and quantum logic relative to qubits, quantum cryptography with many quantum levels, and analog quantum simulations, in which controllable quantum systems emulate the dynamics of other quantum systems and explore new physical phenomena. If two players have been able to "score" so many exciting results in qubit quantum systems, then many players should be able to score even more results and win more challenging matches.

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