metabolically dormant forms that made their way to each habitat through dispersal.

Both studies (*7*, *8*) are consistent with the second model of the rare biosphere. We may thus expect cold-adapted organisms to arrive at hot ocean vents and the microbial gut biota of dugongs (marine herbivores in the Indo-Pacific) to be found in the coastal waters of Vladivostok. But how can we resolve the inconsistency of these demonstrations of the power of dispersal with the molecular evidence of endemism gathered by Hughes-Martiny *et al*. (*6*)? And why is there a discontinuity when microbes and larger organisms are compared?

The answer to the first question is probably straightforward. Taxa, like seashores or clouds, are not discrete objects. This is most dramatically illustrated by prokaryotes, where an entity is a mirage: a shimmering exchange of genetic materials (*10*). What we consider the objects to be depends on the perspective we take. Just as the objects are indefinite, so will much of their biology be indefinite, and our evidence and the stories we tell must be interpreted in an appropriate context. As with all organisms, the distributions of microbes are determined by both history and environment. Any distribution can be seen as more or less endemic depending on the perspective that is chosen. Such a contextualized understanding reveals that biology is less simple than we would like it to be.

To address the second question, we must keep in mind that the phenomena of biodiversity emerge from the interplay of serendipitous evolutionary processes and complex ecological interactions. Their time scales extend from microseconds to millennia, and their physical scales range from nanometers to thousands of kilometers. This gives biology a unique scientific character in which the narrative is as important as an explanatory tool as is reductionism (*11*). Yet, most efforts to find meaning within biology emphasize the examination of the particular, an approach not well suited to discovering large-scale phenomena or unusual emergent properties that are likely to be evident as discontinuities. For these areas, a more macroscopic approach (*12*) has value, as has already been argued in the biodiversity sciences (*13*).

How do we facilitate an approach that will improve on reductionism when it comes to picking up patterns and discontinuities? At least part of the answer lies in the tools used by the current authors (*7*, *8*) and by Sogin *et al*. (*9*). All these tools—whether new molecular technologies or informatics tools—have remarkable scalability. The Encyclopedia of Life (*14*), with a taxonomically intelligent infrastructure that can be applied to all organisms, further confirms that biology can change to include a macroscopic perspective that complements narrative, hypothesis, and experiment. Historically, sweeping statements attracted criticism because they degraded the precision and accuracy of the units of knowledge. In contrast, the new tools not only scale well but retain all details with full fidelity. That is a crucial step forward.

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PHYSICS

Itinerant Ferromagnetism with Ultracold Atoms

Cold lithium atoms undergoing strong repulsions can be driven into a state that is an analog of ferromagnetic ordering.

Wilhelm Zwerger

Ferromagnets, such as those made of iron or nickel, are called itinerant because the electrons whose spins aligned to create the magnetic state are extended and are the same as the ones responsible for conduction. Ferromagnetism was a mystery for classical physics, and its explanation in terms of spin, exchange interactions, and repulsions between identical particles was a triumph of early quantum mechanics. However, it proved difficult to apply these early models to real ferromagnets in a quantitative way, both because the simple models neglect important features relevant in real materials and because theoretical tools to properly treat the strong correlation problem have only recently been developed. Fortunately, the simple models studied in the early days of quantum mechanics can also be applied to fermions other than electrons. On page 1521 of this issue, Jo *et al*. (*1*) provide evidence for an analog of ferromagnetism in an ultracold gas of neutral lithium-6 atoms. When repulsive interactions between these freely moving particles are sufficiently strong, a transition to ferromagnetic ordering is seen.

Heisenberg recognized that exchange interactions between electrons residing in atomic orbitals that overlap spatially could favor a spin-aligned state. The repulsive energy decreases as more spins flip to the majority spin state. Bloch extended Heisenberg's idea (*2*) to delocalized electrons in what is now known as "itinerant exchange" (*3*–*5*). Bloch showed that the ground state of a free electron gas favors full spin polarization at low densities (*2*). The ground state energy per particle depends on k_F, the Fermi wave vector of the gas with an equal number of particles in each spin state. In his model, the fully magnetized state appeared when $k_F a_0 < 0.35$, where a_0 is the Bohr radius. However, the few systems that exhibit such low densities are not ferromagnetic. In fact, precise Monte Carlo calculations suggest (*6*) that the transition to a ferromagnetic state appears at k_F values that are about one order of magnitude lower than the simple Hartree-Fock estimate that Bloch used.

A major conceptual step was taken by Stoner (*7*–*9*), who introduced an exchange field, similar to the molecular field that had been postulated by Weiss. Thus, rather than actually exchanging multiple electrons, the

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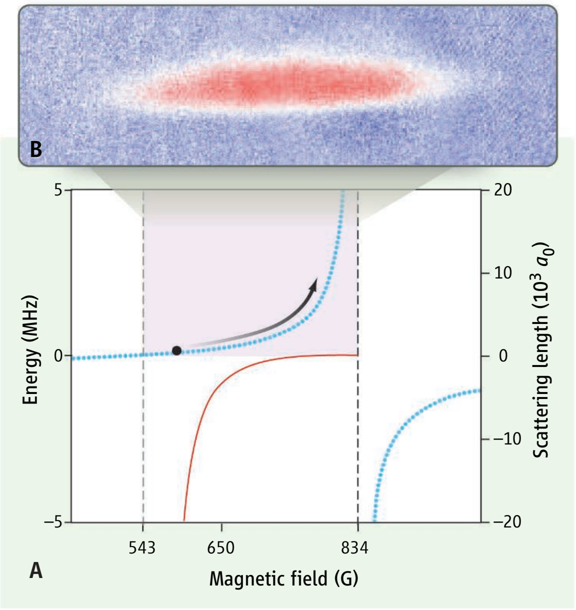
physics could be viewed as the effect of a fluctuating spin environment on a single electron. The simplified model predicts itinerant ferromagnetism for sufficiently strong repulsion parameter *U* or for a high density of states at the Fermi energy. The simple Stoner model and its extensions have been used to describe ferromagnetism in the transition metals like nickel or iron. For quantitative predictions, however, a reliable theoretical determination of the effective *U* turns out to be very difficult.

The problem with applying the Stoner model is that, although magnets can be fairly simple samples experimentally, the electronic structure within them is incredibly complex. The theory can be applied more directly by examining a system that is physically difficult to realize—trapped ultracold atoms in a magnetic field—but that contains neutral fermions, for which the Stoner model of a zero-range repulsion between fermions of opposite spin is perfectly valid. The strategy of Jo *et al.* begins by trapping a gas of lithium-6 atoms in a 50:50 mixture of the two lowest hyperfine states, which are states that arise in the presence of a magnetic field. The population of these states is analogous to the spin states of the electron and is called pseudospin. In contrast to electrons in solids, this pseudospin is conserved because the Pauli principle forbids transitions between the different hyperfine states (*10*). As a result, the total "magnetization" always vanishes; the signature of ferromagnetism is the formation of domains that contain only atoms in one of the hyperfine states.

The relative momenta of two ultracold atoms are so small that only s-wave, or "head-on" collisions occur between different hyperfine states. These collisions can be completely characterized by one parameter, the associated scattering length *a* (*10*, *11*). The ground-state energy of the two-component ultracold Fermi gas derived with a mean-field approximation has a form similar to that derived by Bloch for electrons. However, the negative exchange contribution is replaced by a positive term that comes from the repulsion. When the system becomes a ferromagnet and has only one pseudospin component, this term completely vanishes at the expense of an increase of the kinetic energy. The competition between the kinetic energy that scales like k_F^2 and the repulsion proportional to $k_F^3 a$ favors a ferromagnetic configuration for $k_F a > \pi/2$, which now occurs at high densities.



Atomic models of ferromagnetism. (**A**) Repulsive interactions between ultracold lithium-6 atoms can result in an analog of ferromagnetism. The two lowest hyperfine states are analogs of spin and are called pseudospin states. Tuning of an applied magnetic field creates a Feshbach resonance that increases the repulsion between atoms (the colored region), which is reflected by an increase in their scattering length (shown in blue in units of the Bohr radius a_0). This broad resonance occurs at a magnetic field of 834 G; a narrower resonance occurs at 543 G. The arrow indicates the experimental ramp in magnetic field that beings at 590 G (indicated as a dot). Shown in red is the energy of the competing bound state on the repulsive side of the resonance where $a > 0$. (**B**) The absorption image shows one of the pseudospin states as the field is ramped up at a field of 812 G.

Driving cold atoms into the strong-repulsion regime is challenging. At the low densities typical for ultracold gases, Fermi wavelengths are almost 1 μm. To achieve scattering lengths of this size, Jo *et al.* use a Feshbach resonance in which the collision energy matches the energy of a closed-channel bound state (*10*, *11*). The scattering length can be tuned simply by changing the magnetic field (see the blue curves in the figure, panel A).

One complication occurs when driving the atoms into the strong repulsive regime—this process competes with forming bound molecular states, whose energy is shown in red in the figure, panel A. This bound state can only be reached by three-body collisions, which normally would be rare but unfortunately occur at a high rate near the Feshbach resonance (*12*). In practice, therefore, the lifetime of ultracold gases with strong repulsive interactions is only on the order of milliseconds before molecule formation sets in.

What is the evidence, then, for Stoner-type ferrromagnetism caused by strong repulsion in ultracold gases? Jo *et al.* ramped the magnetic field within a few milliseconds to values near the Feshbach resonance (see the figure). Beyond a critical final value, where $(k_F a)_c \approx 1.9 \pm 0.2$, they observed three of the characteristic signatures expected for a ferromagnetic transition. Inelastic three-body collisions, which require fermions with opposite spin to be close together, were suppressed by domain formation. A minimum was seen in the kinetic energy of the atoms and then rose steeply because of an increase in k_F associated with the atoms forming local domains of the same spin state. In addition, a maximum was seen in the size of the atomic cloud again in qualitative agreement with the Stoner theory of a ferromagnetic transition, in which the ground-state pressure goes down because the fermions avoid the repulsive interaction.

Ideally, the expected ferromagnetic domains could be detected by phase-contrast imaging (*10*). The observed noise, however, was too large, and Jo *et al.* estimate that the domain size reached before molecule formation destroyed the ferromagnetic order was less than 2 μm, or only about 50 atoms in the same hyperfine state.

What are the perspectives opened by these intriguing results? Clearly, cold gases lack most of the complexities that still make ferromagnetism in real materials an open challenge in condensed matter physics. Yet, the simplicity of cold gases, and in particular the tunablity of interaction strengths, makes them an ideal tool to understand basic many-body problems that have remained open for decades. In particular, it is unknown beyond simple approximations like that of Stoner whether the strongly repulsive Fermi gas in the continuum has indeed a ferromagnetic ground state.

Cold atoms are thus a kind of quantum simulator that allows solving problems that are intractable otherwise. When cold atoms are also confined with optical lattices, magnetism would arise through superexchange induced by tunneling between nearest neighbor localized sites. Despite the small energy scales involved, superexchange has recently been realized with bosonic atoms (*13*). With fermionic atoms, this kind of system opens the way to investigate the predicted occurrence of ferromagnetism in the repulsive Hubbard model in three dimensions or, more generally, the competition between ferromagnetism and superconductivity near quantum phase transitions (*14*). Of particular interest is also the two-dimensional case where antiferromagnetism competes with d-wave superconductivity, a key issue in

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models that are used to describe high-temperature superconductors.

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GEOPHYSICS

How River Beds Move

Philippe Frey[1] and Michael Church[2]

Insights into sediment transport at river beds can come from experiments in granular physics.

The transport of sediment through river channels has major consequences for public safety, management of water resources, and environmental sustainability. Most studies of sediment transport in rivers have focused on mass flux and its relation to water flow. Yet, after more than a century of work, there is no satisfactory theory for bedload, the component of the sediment load transported in contact with the stream bed. Bedload transport formulae often overpredict the actual rate by orders of magnitude (*1*). It is therefore difficult to predict, for example, the impact of disturbances such as extreme floods on the channel. Better insight may come from viewing bedload as a granular phenomenon.

Bedload transport can be divided into two stages (*2*): partial mobility of local bed surface material when part of the bed remains static but exposed grains may eventually move, and full mobility, when all grains move to a depth of several grain diameters. Grain-grain interactions over short time and length scales bear importantly on the predictability of both stages.

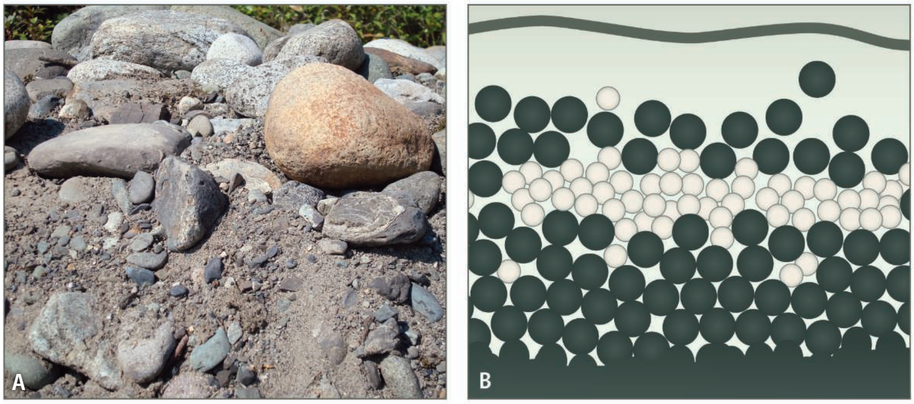
No single constitutive law reproduces the diversity of behaviors of cohesionless granular materials (*3*). Granular flows are often classified into three states: a gaseous state, in which flow is very rapid and dilute, and the particles interact by collision; an intermediate state, in which the material is dense but still flows like a liquid, the particles interacting both by collision and friction; and a dense, quasistatic state, in which the deformations are very slow and the particles interact by frictional contacts. All three states might be found in free surface flows and in bedload.

Probably the most important phenomenon relevant to bedload is size segregation by shearing in free surface flows. Two distinct size segregation phenomena occur. When the coarsest fractions of the bed do not move and the smallest fractions are sufficiently fine, spontaneous percolation occurs. But when the bed is moving, kinematic sieving of the finer particles take place even if the size ratio is close to unity (*4*, *5*). The usual result is a downward flux of smaller particles and an upward flux of larger particles, resulting in the segregation observed in river deposits (see the figure, panel A) and in a substantial reduction in transport.

Velocity and concentration profiles provide insight into the rheology of the granular flow. Regardless of grain sizes, interstitial fluid densities, and viscosities, the mean granular velocity profile has a similar shape, with a linear profile in the upper part and an exponential decay toward zero in the lower part (*6*). Velocity fluctuations permit computation of the granular "temperature" (the sum of streamwise and vertical variances of instantaneous velocity), a variable central to kinetic-theory modeling of low-density granular flows (*7*). In a study of size segregation (*8*), Hill and Zhang have shown that granular temperature profiles were particular to a size class, whereas mean velocity profiles were not.

Important differences between granular motion, as usually studied in both research and industrial contexts, and bedload transport in rivers include the very wide range of grain sizes and shapes normally present in fluvial sediments; the highly irregular geometry of river channels (itself a consequence of the movement and deposition of bed material); the highly variable forcing in rivers, both temporally and spatially; and the generally lower rates of flux. Nevertheless, important analogies may be exploited.

In rivers, full mobility is usually observed in sands, but also occurs in gravels under sufficiently strong flows. Few studies have addressed particle velocity and concentration profiles in full-mobility bedload (*9*, *10*). The measured profiles have the same shape as their dry granular counterparts. Such results have been successfully compared with models of collisional grain flows based on kinetic theory or dense flow rheology (*3*, *11*). As to segregation, bedload studies usually investigate the spontaneous percolation of fine grains into immobile gravels (*12*). In an experimental study, smaller beads have been introduced



Segregation through motion. (A) This vertical profile in a gravel river bar (in Vedder River, British Columbia, Canada) shows size sorting with an armored surface and finer material below. **(B)** In a quasi–two-dimensional experiment (*13*), kinematic sieving leads to the formation of layers of smaller transparent beads under larger moving black beads. This panel was redrawn from a video snapshot.

CREDIT: (PANEL A) PHILIPPE FREY/CEMAGREF

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