surate with the layer thickness, one is left with a beat period. This beat period appears in transport properties such as magnetoresistance (*3*).

The discrete electronic structure of a thin metal film was first observed experimentally via the tunnel current across a metal-insulator thin-film sandwich (*4*). Because the film served as an electrode, it had to be conducting, which meant that the thickness had to be at least ~10 nm. Later work demonstrated that photoelectron (*5*, *6*) and scanning tunneling spectroscopies (*7*) are powerful tools to probe the electron states in thin adsorbed films down to monolayer thicknesses.

When the adsorbed film is only few atomic layers thick, the boundary conditions are particularly important. If a film is taken from vacuum and placed on a substrate, then it matters what the substrate is. Within a substrate energy gap (an energy range in which no valence electrons are found and which is often referred to as "forbidden"), one may find discrete quantum well–like states in the film. These states extend into the substrate, but only with an oscillating tail, with the period given by the substrate lattice. The decay depth of the state is given by the energy of the state with respect to the edges of the energy gap, the tails being long near the edges. The electronic state is thus a hybrid with a distinctly different character in the film and in the substrate.

Speer *et al.* have now used photoemission spectroscopy to study quantum-well states in silver films deposited on silicon. The silver films are 8 to 12 atomic layers thick. At these thicknesses, one would not expect the choice of substrate to be important for the ladder of energy bands. For example, nearly the same quantum-well state energies are observed when silver films are adsorbed on gold (*8*) as on the silicon substrate used by Speer *et al*. But as Speer *et al*. show, a dramatically different set of states can be obtained by increasing the doping of the silicon substrate.

When the Ag film and n-type Si are brought in contact, equilibrium (coincident Fermi levels) requires a transfer of electrons from Si to the metal. Near the interface, the semiconductor is depleted of electrons and the electron states are shifted in energy with respect to the states in the bulk. The depth dependence of the energy is referred to as band bending (*9*). With high n-doping (see the figure, right), the band bending saturates at a depth that is shallow enough for a novel set of discrete states to form. The electrons that form these states encounter the confining substrate band gap within the substrate and not at the interface. This means that the quantum well becomes wide, ranging from the vacuum interface to the depth where the energy coincides with the lower edge of the gap. The states therefore become less separated in energy than the standard type of quantum-well states.

The results reported by Speer *et al.* provide a detailed image of the electronic structure at a metal-semiconductor junction. The authors can account for their observations with simple models that can easily be extended to overlayers with different thickness and to substrates with different impurity content, or where the band bending may be changed by illuminating the interface (*10*).

Given the long and troublesome history of accounting for the properties of metal-semiconductor junctions (*11*), it is encouraging that there are cases in which simple modeling does not appear to be hampered by the occurrence of defects, intermixing, or compound formation at the interface. Furthermore, the effects reported by Speer *et al.* could be used to systematically modify the quantized electronic structure of thin film systems, thereby providing a powerful means for tuning properties of interest.

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ECOLOGY

A Renaissance in the Study of Abundance

Brian J. McGill

Ecologists have borrowed a powerful tool from physics to calculate how environmental constraints affect the abundance of species.

In the drainage basin of one small river in the center of the North American continent, one can find Kirtland's warbler, which has a total population that seems to fluctuate around a few thousand individuals. In that same area, or indeed almost anywhere else east of the Rocky Mountains up until about 200 years ago, the passenger pigeon thrived with a total population size estimated in the low billions (*1*). This six-orders-of-magnitude discrepancy begs an explanation, especially once we notice that this seems to be one of ecology's few universal laws (see the figure). Every ecosystem in the world, whether at the bottom of the sea or the middle of the Amazonian rain forest, has a few hyperabundant species and many relatively rare species (*2*). Understanding why a species has a particular abundance is the embarrassing and obvious question that ecology cannot yet answer.

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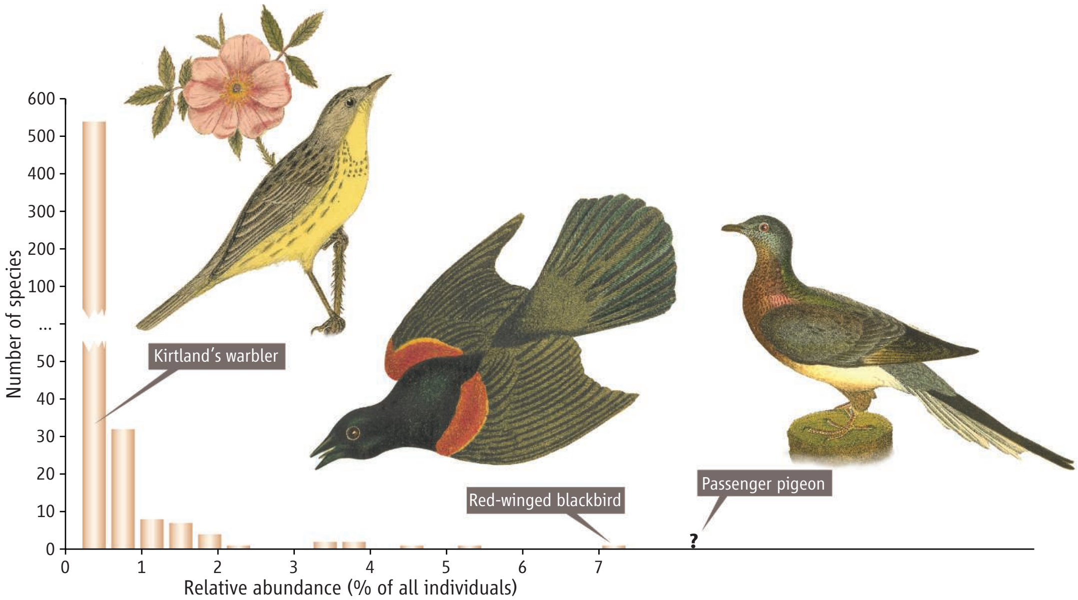
On page 812 of this issue, Shipley *et al.* take a good first step toward an explanation (*3*). The setup is simple. Twelve vineyards were abandoned in southern France over a period ranging from 2 to 42 years ago. These yards slowly returned to natural vegetation, and the relative abundance (percentage of the total plant population $p_1 \ldots p_{30}$) of 30 plant species in these plots was counted. The authors also measured a suite of eight characteristics or traits, such as perennial versus annual, thickness of leaf, and height of plant for each species ($t_{\text{trait,species}}$), for a total of $240 = 8 \times 30$ trait measures. They then calculated the average values of these eight traits ($t_{\text{trait},*}$) for each vineyard as a whole, using the equations:

$$\begin{aligned} t_{\text{height},*} &= p_1 t_{\text{height},1} + \ldots + p_{30} t_{\text{height},30} \\ &\ldots \\ t_{\text{leafthickness},*} &= p_1 t_{\text{leafthickness},1} + \ldots + p_{30} t_{\text{leafthickness},30} \end{aligned} \quad (1)$$

Next, Shipley *et al.* showed something elegant: These average traits show orderly change over time as the vineyards return to nature (see their figure 1). They hypothesize, although they do not directly test, that this is due to what they call environmental filtering—for any given environmental context (including field age), there is an "optimal" value for the traits, and species with trait combinations close to this optimum fare better. At this juncture, Shipley *et al*. took a radical departure and did something that ecologists loathe; they borrowed a tool from physics. And not just any tool, but a tool that is still shiny and new in physics called entropy maximization (EM).

Physicists revel in the idea that most of their laws can be reduced to optimization principles (e.g., Lagrange's law of minimum "action" supplants Newton's three laws of motion). It has recently been shown that EM can replace a supercomputer with just a few lines of calculations for modeling how the unequal arrival of solar energy gets redistributed by the atmosphere and oceans (i.e., weather). And this works not only for Earth but for Saturn's moon Titan. This has catapulted EM to prominence in the physical sciences (*4*) after lying on a back shelf for 40 years (*5*). But ecologists who study communities of species tend to regard maximization principles as disreputable (for some good reasons).

Against this context, Shipley *et al.* boldly apply the EM principle in ecology to predict abundances. EM starts with constraints (what is known about the system) and fills out the rest (our ignorance) by maximizing entropy. The environmental filtering hypothesis used by Shipley *et al*. asserts that traits constrain communities such that abundances are chosen to produce average traits ($t_{\text{trait},*}$) optimal for the given environmental conditions (Eq. 1 in reverse). From high school algebra we know, however, that starting with only eight traits (i.e., equations or constraints) and trying to predict 30 species abundances p_i (i.e., unknowns) is an underdetermined problem; there are an infinite number of solutions arrayed across a 22-dimensional space (22 = 30 – 8). Some additional rule is needed to pick from this infinitude of possible answers. Here is where entropy steps in. Entropy is best thought of as evenness (even distribution of heat across a planet, or even abundances across species, i.e., $p_1 = p_2 = \ldots = p_{30}$). With the mathematical technique known as Lagrange multipliers used to maximize entropy, the predicted relative abundances for all 30 species (equation 5 of Shipley *et al*.) pop right out. The method works so well that Shipley *et al*. can explain 96% of the variation in relative abundances of each species, the kind of result that ecologists usually only lust after.



Wildly different. The bar graph shows a histogram of the relative abundances of more than 500 bird species from the Breeding Bird Survey (*14*), which counts every bird encountered at more than 1400 points across North America. The horizontal axis is relative abundance (percentage of total individuals observed) binned into groups, and the vertical axis indicates the number of species falling into each group of abundances (note broken axis). The left bird is Kirtland's warbler, which falls in the lowest group of abundances. The bottom right bird is the passenger pigeon, which is now extinct but would have been placed off the right end of the graph. The center bird is the red-winged blackbird, which is now the most abundant bird in North America and is 400,000 times more common than the 16 rarest birds in the leftmost bin.

CREDIT: KIRTLAND'S WARBLER, C. J. MAYNARD; PASSENGER PIGEON AND RED-WINGED BLACKBIRD, ALEXANDER WILSON

Why it works is harder to explain. In statistical mechanics entropy has a clear meaning, but in ecology it is a vague concept (despite having been used for years as a measure of evenness). Whether entropy represents species acting randomly and individualistically or communities acting to maximize a collective property such as energy transformation is really just new words in a long-running debate in ecology (*6*).

The report by Shipley *et al*. is exemplary of a more general renaissance occurring right now. The study of abundance had been stuck on three classical approaches: (i) using differential equations to describe the population dynamics of a species has proven good at explaining the variation in abundance of one species over time (that is what differential equations do, after all) but poor at predicting different abundances between species; (ii) finding correlations between traits and abundance has largely failed (*7*), probably because of the focus on one trait at a time, until the work of Shipley *et al*.; and (iii) relying on purely stochastic explanations (each species' abundance is set by a roll of Mother Nature's dice) fails to explain why relative abundances can stay constant for a million years (*6*) or why abundances bounce back almost immediately to formerly high levels after spending a couple of thousand years near extinction while fighting off a pest (*8*).

These classic approaches began to be left behind as the study of abundance was reinvigorated 5 years ago with the introduction of neutral theory (*9, 10*). Neutral theory is an elegant theory that makes strong predictions about abundance but rejects two ideas dear to ecologists: the importance of the environmental context and of species differences (traits). Ecologists have fought back by falsifying neutral theory (*11*) but have not yet put up a fair fight by giving an alternative theory that makes equally strong predictions about abundances while incorporating traits and environment (*12*). Shipley *et al.* just may have made the fight fair.

Other fundamental questions about abundance are finally beginning to be explored as well, such as (i) why abundance varies by about two orders of magnitude across space within a single species, (ii) why abundance of a species changes with temperature, (iii) why abundance and range size are so strongly correlated, (iv) why naturally (not human-caused) rare species such as Kirtland's warbler persist so long, and (v) what factors cause the (always large) portion of rare species to vary by small amounts. This renewed interest cannot come too soon. Understanding abundance is critical to conservation and global change. It is about time that ecologists start to deliver on our claim that we study "the distribution and abundance of particular species" [(*13*), p. 3].

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ASTRONOMY

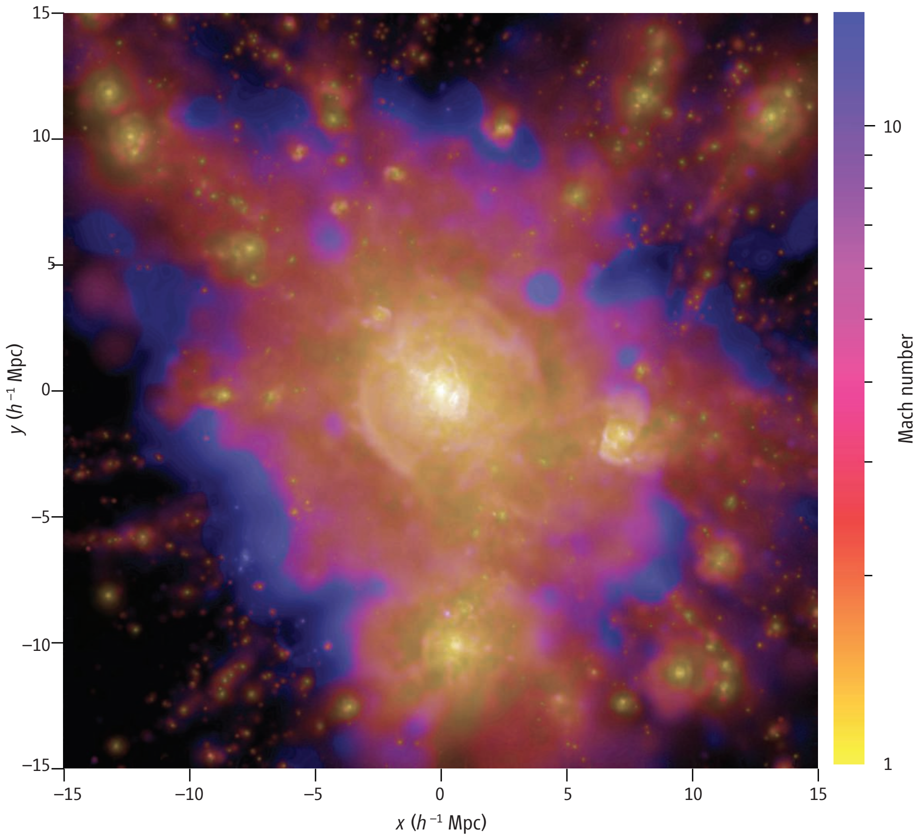
Radio Traces of Cosmic Shock Waves

Colliding and fusing galaxy clusters should produce giant shock waves. The outlines of these waves have now been seen as radio-emitting structures.

Torsten A. Enßlin

The distribution of galaxies in the universe is marked by vast cosmic voids embraced by a network of galaxy filaments and massive galaxy clusters containing up to thousands of galaxies. This inhomogeneous matter distribution emerged from an extremely smooth initial state created by the Big Bang, with relative density fluctuations of only 10^{-5}. This remarkable smoothness was first revealed by the work of the COBE (Cosmic Background Explorer) team, work that was awarded the 2006 Nobel prize in physics. Over billions of years, the initially tiny density variations grew drastically through gravitational attraction of neighboring matter. Larger and larger structures still form today as a result of the violent merging of galaxies and clusters of galaxies. In addition, there is a continuous accretion flow of gas falling onto galaxy clusters out of the dilute intergalactic medium. On page 791 of this issue, Bagchi *et al*. (*1*) report the detection of giant radio structures around a galaxy cluster that probably trace shock waves caused by such energetic collisions, mergers, and movement of gas.

Gas falling into the gravitational wells of galaxy clusters can reach velocities of up to a few thousand kilometers per second. When it collides with the hot and ionized gas at a temperature of 10^7 to 10^8 K within clusters, shock waves form and heat the infalling gas to similar temperatures. Magnetic fields in the gas may permit a small fraction of the thermal gas particles to scatter back into the upstream region of the shock wave and to undergo the energizing shock compression again and again. This so-called diffusive shock acceleration process produces nonthermal particles with an energy spectrum easily extending to ultrarelativistic energies, where particle energies exceed their rest mass energies by large factors. Although the number of these relativistic particles is small compared with the thermal ones, they can account for a substantial fraction of the dissipated shock energy.



Energetic events. Energy dissipation by cosmic shock waves around a massive galaxy cluster and two smaller infalling systems in a numerical simulation. The brightness scales logarithmically with the dissipation rate, the colors indicate the (dissipation weighted) shock Mach numbers. Although most of the energy dissipation occurs within a few megaparsecs around the cluster centers, the surrounding accretion shock waves have the highest Mach numbers (blue structures). A pair of merger-induced shock waves can also be seen roughly 3 Mpc away from the center of the main cluster.

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