dressed by further population genetic studies).

Regardless of the exact process that led to the *S. aureus* population structure in the Oxford community, the Day *et al.* work has exciting implications for future research. Their findings suggest an answer to the riddle of why *S. aureus* has evolved mechanisms for causing disease when disease is not a necessary or even a common part of its life cycle—the same features that make this commensal a good colonizer also make it better at causing disease. This hypothesis can be evaluated experimentally by, for example, testing avirulent and hypervirulent mutant strains for features that affect colonization, such as adherence to epithelial cells. Day *et al.* found that recombination at three of the seven loci in particular was associated with a loss of virulence, suggesting that genes for virulence factors may be present near these loci. Identification of particular genes that are associated, at the population level, with virulence and the ability to colonize hosts (*5*) will provide candidate virulence factors whose effects on colonization can be tested.

Epidemiologists and researchers that study how microbes cause disease have been skeptical about the relevance of evolutionary biology and population genetics to their disciplines. This is starting to change as researchers recognize the importance of pathogen population structure for antimicrobial resistance (*6*), interactions between pathogens and the immune system (*7*), identifying candidate antigens for vaccines (*8*), and predicting (*9*, *10*) and assessing (*11*) the effectiveness of vaccination programs. The work of Day *et al.* shows that studies of the population genetics of an infectious agent can generate hypotheses about microbial pathogenesis that are both new and experimentally testable. It also demonstrates that a complete understanding of the epidemiology and transmission of infectious diseases depends on a clear picture of the population genetic structure of the causative organism.

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PERSPECTIVES: OPTICAL MATERIALS

Bending Light the Wrong Way

M. C. K. Wiltshire

The refractive index is a basic property of optical materials. It is a measure of how much light slows down when it enters a medium and accounts for the familiar "bent stick in water" phenomenon. This property determines the behavior of lenses and prisms and underpins all optical instrument design. Air and vacuum have a refractive index n of 1, the n for glass is typically between 1.5 and 1.8, and other materials may have n as high as 2.2. This property is not restricted to light waves. Semiconductor materials have a high refractive index in the infrared (for example, $n = 4$ for germanium), and at microwave and radio frequencies, lenses can be made of Teflon. But n is always positive and is normally greater than 1. So what do Shelby *et al.* mean on page 77 of this issue (*1*) when they say that they have verified the existence of negative refractive index materials?

To see how a negative refractive index can arise, we have to go back to Maxwell's equations (*2*) describing the behavior of electromagnetic radiation. These equations relate the behavior of electric and magnetic fields to the dielectric and magnetic properties of the ambient medium, captured respectively by the relative permittivity ε and relative permeability μ. The combined equations predict a wave motion propagating at a speed of $1/\sqrt{(\varepsilon\varepsilon_0\mu\mu_0)}$, where ε_0 and μ_0 are the permittivity and permeability, respectively, of the vacuum. The refractive index of the medium is $n = \sqrt{(\varepsilon\mu)}$.

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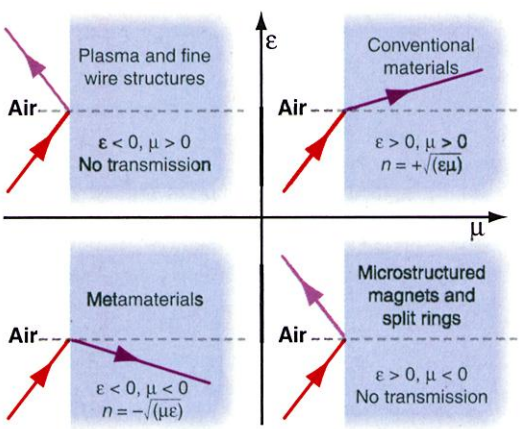
In the 1960s, the Russian theoretician Veselago (*3*) classified materials according to their ε and μ (see the figure). He realized that it was possible to have negative ε and negative μ and still achieve a propagating wave because $(\varepsilon\mu)$ would be positive. However, to ensure conservation of energy he had to take the negative sign of the square root, which we now interpret as giving a negative refractive index. This meant that light would bend the "wrong" way: Positive lenses would become negative, flat sheets could focus, the Doppler effect would be reversed, and other counterintuitive phenomena would occur. The only problem was that materials with negative n did not exist.



Going beyond convention. Materials can be classified in terms of the sign of their permittivity ε and permeability μ. For each of the possible four cases, the behavior of radiation incident on an air-material interface is shown. In the case of conventional dielectric materials (top right quadrant, with positive ε and μ and thus positive n), the refracted ray lies closer to the normal than the incident ray. Plasmas with negative ε (top left quadrant) reflect radiation. Microstructured magnetic materials with negative μ (bottom right quadrant) also block radiation. The metamaterials (bottom left quadrant, with negative ε and μ and thus negative n) refract to the opposite side of the normal.

The solution lies with artificial optical materials, which provide the scope to tailor an electromagnetic response. If the materials are microstructured and all their constituents are much smaller than the wavelength of the radiation that they interact with, they can be described accurately by their permittivity and permeability. Pendry and co-workers (*4*, *5*) have shown that structures built from fine wires mimic a plasma and have a negative ε in the microwave regime. They have also proposed structures (*6*) that could exhibit negative μ. Shelby *et al.* realized that combining these structures into one "metamaterial" should lead to a material with negative ε and μ. Last year (*7*), they showed proof of principle; now they report the definitive experiment (*1*).

The refractive index of a material is determined by measuring the deviation of light at its surface. Shelby *et al.* did so with their metamaterial at microwave frequencies (10.5 GHz). First, they built a two-dimensional material (*8*) from split rings and fine wires, all based on printed circuit boards. This bulk material was cut into a prism, and microwaves were shone through it and their deflection measured. A Teflon prism was used as a reference. The result is striking: The Teflon prism bends the microwaves in the usual way; the metamaterial bends them the other way (see the figure). It has a negative refractive index.

It is clear from Veselago's and more recent work that a negative refractive index leads to some very strange optics. For example, Pendry (*9*) has shown theoretically that a negative material could out-perform a conventional lens because it acts not only on the propagating rays that are controlled by conventional optics but also on the evanescent waves, which decay rapidly with distance and cannot be accessed by conventional imaging optics. All the information about the source could thereby be brought to the focus: We would have the perfect lens. For the first time, Shelby *et al.*'s material, when fully optimized to reduce loss, provides the opportunity to validate this extraordinary concept.

These ideas are not confined to microwave frequencies. We have shown (*10*) that microstructured "Swiss Roll" materials can have enhanced positive or negative permeability at radio frequencies (~20 MHz). Shelby *et al.* suggest that it may be possible to make metamaterials for the infrared but consider it unlikely that viable materials in the visible will be achieved. The materials may nevertheless find a wide variety of applications, but it is perhaps too early to say where we shall first see them used.

But what about the speed of light? Does a negative refractive index mean that light travels backward? Not in any conventional sense. The metamaterial is highly dispersive; that is, its refractive index varies rapidly with frequency. This results in a difference between the group velocity of light, which measures the speed at which information or energy is transported, and the phase velocity, which measures the speed of the individual light wavefronts. The wavefronts do indeed move backward, consistent with the negative n, but energy is still transported forward. Hence, the materials do obey the laws of physics while opening up new possibilities for manipulating radiation.

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PERSPECTIVES: ATMOSPHERIC SCIENCE

Solving the PSC Mystery

Margaret A. Tolbert and Owen B. Toon

Lurking in the depths of the polar night poised to activate chlorine for ozone destruction, most polar stratospheric clouds (PSCs) are never seen from Earth, although they can have a vertical extent and breadth comparable to that of the United States. Long considered a curiosity, they became infamous after the ozone hole was discovered. Recent field campaigns are beginning to shed light on the composition of these clouds and the mechanisms by which they affect stratospheric composition and chemistry.

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Nacreous clouds resembling giant abalone shells floating in the sky are a form of PSCs formed by wind flow over mountains. These opalescent clouds have been reported sporadically for over a hundred years from Scandinavia, and Edward Wilson noted them on Robert Falcon Scott's 1901 Antarctic expedition (see the first figure) (*1*). In the mid-20th century, scientists measured their altitudes over Scandinavia near 25 km and showed that water vapor condenses in stratospheric mountain waves at temperatures near –80°C to form micrometer-sized ice particles (*2*, *3*). The beautiful pink and green coloration of the clouds in the twilight sky was shown to result from forward diffraction of sunlight by the particles, whose size distribution is locally nearly monodisperse but whose mean size varies along the profile of the wave.

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A colorful curiosity? This drawing by Edward Wilson, "Opalescent alto stratus and snow drift," shows the sky and clouds at McMurdo Sound, Antarctica, 17 August 1903. His diary notes "If a dozen vivid rainbows were broken up by a heavy wind and scattered in wavy ribbands and flecks of curl and fleecy cloudlike forms ... we would have something like the beautiful appearance of this cloud colouring" (*1*).

With the advent of satellites came the recognition that PSCs were common in the polar winter, particularly above Antarctica (*4*). Still, PSCs were considered essentially irrelevant for atmospheric chemistry and climate until Farman *et al.* discovered the Antarctic ozone hole in the mid-1980s (*5*).

Like a murder mystery, the discovery of severe ozone loss above Antarctica was accompanied by distinct clues, some of which were red herrings. Solomon and co-workers were the first to identify the essential clues (*6*, *7*). The ozone loss occurred in the only place on Earth cold enough for clouds to form in the stratosphere (where most ozone is located), in spring when sunshine was available, and during an epoch when chlorine levels in the stratosphere were reaching record levels. They postulated that chlorine was converted from the inert "reservoir" species $ClONO_2$ and HCl to active species by heterogeneous reactions on PSCs. The active chlorine species could then react catalytically with ozone as long as sunlight was present (see blue arrows in the second figure). Laboratory studies quickly provided the rates of key heterogeneous reactions on PSCs. The overall mechanism was confirmed in a series of field campaigns, which showed conversion of chlorine from reservoir to reactive species near PSCs and unprecedented concentrations of reactive chlorine in conjunction with severe ozone loss.

Other clues in the ozone loss mystery suggested that condensed HNO_3 was an important component of PSCs (*8*, *9*), and nitrate was soon detected in them (*10*, *11*). Laboratory work (*12*) showed that nitric acid trihydrate (NAT) was the thermodynamically stable form of HNO_3/ice in the polar stratosphere. The Antarctic stratosphere is "denitrified" when HNO_3 is permanently removed through sedimentation of large PSC particles. Denitrification removes gaseous nitric acid that could otherwise interrupt the catalytic ozone loss cycle by reforming the reservoir species $ClONO_2$ (see the red arrows in the second figure) (*8*). But denitrification is not the only way to keep chlorine in its active forms. Portmann *et al.* (*13*) have argued that because low temperatures are maintained in the Antarctic vortex until well past the spring equinox, reactivation of $ClONO_2$ on PSCs or dilute liquid sulfate aerosols yields ozone loss

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