"chamber of doom" for its ruthless chopping of proteins, is now also implicated in the creative activity of joining shorter peptides into a longer peptide (*8*). A possible explanation for this function might be that, like all enzymes that catalyze reactions in one direction, it can—in principle and under some circumstances—catalyze the same reaction backward. Alternatively, specific sequence or structural features of the final peptide itself, or its flanking and/or intervening amino acids, might favor the splicing reaction. Further experiments are needed to resolve how proteasomal splicing works.

Irrespective of the still obscure rules for making noncontiguous peptides, their existence shows that genetic information can be scrambled and yet be useful. Cells do not simply discard scrambled peptides, and, like defective or cryptic translation products, use them to add to the pMHC I repertoire (*2*, *9*). This view implies that such scramblings are not random accidents and would have to be generated in other cell types as well. In particular, cells constituting immune organs that are responsible for eliminating self-reactive T cells must generate the same scrambled peptides. This is to ensure that autoimmunity will not result from the sudden appearance of previously unseen pMHC I in some tissues. What fraction of the total pMHC I repertoire represents cryptic translation products or spliced and scrambled peptides, and whether and how they might be regulated, remain important unanswered questions. Nonetheless, it is clear that peptides from these sources are a functional aspect of the antigen presentation mechanism that keeps an eye on the genome, including its unexpected and unpredictable products.

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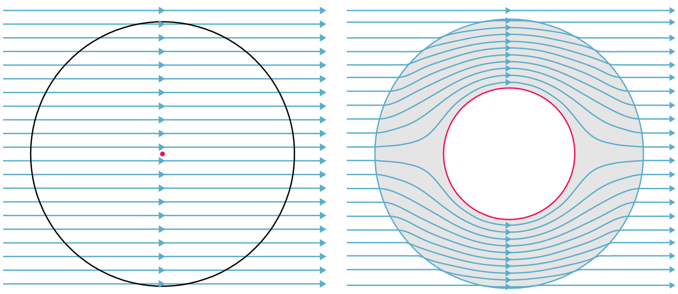
APPLIED PHYSICS

Waves on the Horizon

Emerging materials can influence the dissipation, dispersion, and refraction of light, producing resonant effects that allow intricate control of electromagnetic waves for new applications.

Ping Sheng

The ability to localize waves and create artificial structures capable of manipulating waves are arguably two of the most important developments in optical physics during the past few decades. These advances have been made possible by the fabrication of photonic and phononic crystals (periodic structures that modify the characteristics of photons and phonons, creating frequency band gaps in which no waves can propagate), as well as metamaterials (in which wave properties beyond those intrinsic to the underlying component material properties can be structurally induced). A recent conference of the Optical Society of America (*1*) brought together researchers working in these two areas and highlighted the latest advances. If Lord Rayleigh, who laid the groundwork for much of wave physics a century ago, were alive and had attended the meeting, he might even be surprised to find that what were formerly regarded as "constraints" in wave studies have been knocked down, uncovering new territory in science and technology. In particular, the index of refraction can now take both positive and negative values, waves can be manipulated in ways not thought possible before, and multiple scattering can cause a wave to alter its basic character while retaining phase memory.



Hidden realms. (**Left**) Blue lines indicate the flow of electromagnetic energy through a region of space. (**Right**) The shaded region has been subject to a coordinate transformation. The center of the region denoted by the red dot at left is transformed to the red circle. The region inside the red circle is cloaked and cut off electromagnetically from the region outside. Outside the shaded area, the flows are identical in both panels, implying electromagnetic nondetectability of objects inside the cloaked region.

Maxwell's equations contain two material parameters, the dielectric constant ε and magnetic permeability μ. If the material is anisotropic, ε and μ are 3×3 matrices in general. Under a coordinate transformation, the form of Maxwell equations should remain invariant, but ε and μ would carry the information regarding the original values plus the relevant coordinate transformations. If all the values and anisotropy characteristics of ε and μ are physically realizable, as implied by the advent of metamaterials, then theoretically one can access the many possibilities afforded by the coordinate transformations. Leonhardt (*2*) and Pendry *et al.* (*3*) have pointed out one such possibility that might have come from *Star Trek*—electromagnetic cloaking. The idea is to create a "hole" in the transformed coordinate system in which an object (or objects) can be hidden from detection (see the figure). The hole is not an electromagnetic vacuum but rather a complete separation of electromagnetic domains into a cloaked region and those outside. A cloaked object thus cannot communicate with the outside, and vice versa. A different form of cloaking has also been proposed by Milton and Nicorovici (*4*). By considering a polarizable line dipole in the vicinity of a coated cylinder with core dielectric constant ε_c and surface coating dielectric constant $\varepsilon_s = -\varepsilon_c$, they have shown that under the action of an external quasistatic transverse magnetic field, both the coated cylinder and the polarizable line dipole are invisible—that is, in the cloaking region, the polarizable line dipole produces no induced dipole moment. The reason for this strange behavior is that any induced moment would be

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canceled by the resonant response of the coated cylinder. Otherwise, the energy can diverge (*4*, *5*). Because a single polarizable line dipole produces no induced moment, it follows that a collection of such objects would also produce no moment, and hence be invisible.

To realize all these possibilities requires ingenious materials design supported by advances in technology. There is a plethora of reported advances in both wave-functional materials fabrication, as well as the realization of related phenomena. Because many of the wave-functional effects are associated with resonances, overcoming the limitations imposed by dissipation and dispersion effects (meaning that the desired phenomena are realizable only within a narrow frequency window) represents the most urgent challenge. In this respect, the successful achievement of a photonic crystal optical cavity Q value on the order of 10^6 by Noda's group in Kyoto University (*6*) is noteworthy for foreshadowing the potential applications. There are also efforts to realize a negative refraction index through structural means, such as extreme anisotropy (*7*) and chiral materials (*8*), in addition to photonic crystals. An interesting proposal is to compensate the resonance-induced dissipation with an optical gain medium (*9*), which can be pumped separately. The degree to which these efforts are successful would set the scenario of future wave technology.

Wave localization in the Anderson sense (that is, localization of waves as they scatter in a random medium) is generally characterized spatially by an exponentially decaying wave function. However, if one uses a pulse to probe a medium with localized states, then it can be shown theoretically that there are also characteristic time-domain signatures (*10*). Recent experiments by Storzer *et al*. (*11*) have shown that by measuring time-resolved photon transport through TiO_2 powder samples, one can detect clear deviation from the diffusive behavior that is expected from multiple scatterings (*12*). Moreover, it was reported during the meeting that the deviation can be explained by a time-dependent diffusion constant D that approaches a ~$1/t$ behavior. If $r^2 \sim Dt$, then heuristically $D \sim 1/t$ implies a saturation length—the localization length. The photon mobility edge, the optical analog to the electronic metal-insulator transition, may be within reach.

Random systems are usually characterized by probability functions. Thus, wave localization, a manifestation of multiple scattering of waves in random media, has been mostly studied by focusing on the mean behavior, just as diffusion is the mean behavior of a random walker. A shift away from this focus is represented by the study of the "connectivity" of localized wave functions in a single (finite) random configuration. In a one-dimensional layered system, a connected state consisting of multiple localized wave functions (*13*) with roughly the same energy and equally spaced across the sample is denoted a "necklace." Such necklaces would carry most of the wave flux through the sample, because they represent short circuits in an otherwise insulating sample. In two separate experiments, one in the microwave regime by Sebbah *et al*. (*14*), and one in the optical regime by Bertolotti *et al.* (*15*), these necklace states in a one-dimensional layered system were observed. The true significance of these states may lie in the three-dimensional mobility edge, where in analogy with percolation the connected localized states would play a role similar to that of the percolating backbone, which has density measure zero (because of its fractal geometry) but nevertheless carries all the flux.

As the title of the meeting "From Random to Periodic" implies, some convergence of the two developments may be inevitable, or even anticipated. Challenges remain, however, in identifying the nontrivial intersections, from which new physics and phenomena may emerge.

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PHYSICS

Entangled Solid-State Circuits

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Quantum tomography is used to determine the entangled state of two coupled superconducting qubits, a step forward for solid-state quantum computing.

A fundamental tenet of quantum mechanics is the idea that two spatially separated objects exhibit correlations in observable physical properties that cannot be explained by any classical theory. Troubling even Einstein, this "spooky action at a distance" (*1*)— known as entanglement—is fundamental to quantum information science and directly related to the enhanced computing power of a processor based on quantum bits (qubits). What is remarkable is that solid-state electrical circuits containing as many as 10^{11} atoms can be engineered to exhibit quantum behavior and are well described by the quantum formalism originally developed for individual atoms and photons. One can construct such qubits from thin films using conventional semiconductor fabrication techniques, making them attractive for eventually realizing a quantum computer with many qubits.

With these solid-state "atoms on a chip," one can prepare arbitrary superpositions of single-qubit states and manipulate them with microwave radiation to observe clear signatures of quantum coherence familiar in atomic physics and nuclear magnetic resonance (*2*–*5*). Coupling two or more qubits together results in entangled states with energy spectra that exhibit features such as avoided crossings (*6*) predicted by quantum mechanics. Verifying that two qubits are unambiguously entangled is, however, a delicate task and requires sophisticated benchmarks such as quantum state tomography (*7*). This method involves a series of measurements (analogous

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