Selecting the Direction of Sound Transmission

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APPLIED PHYSICS

Selecting the Direction of Sound Transmission

A device containing a circulating fluid breaks the symmetry of acoustic waves and allows one-way transmission of sound.

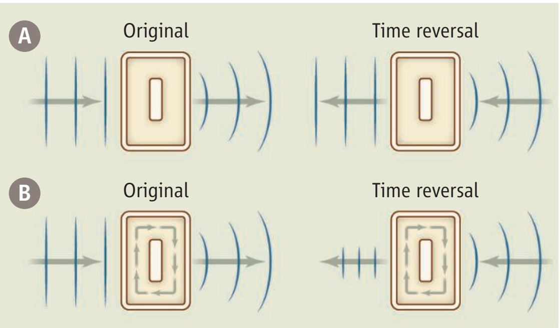
Steven A. Cummer

Structures that admit flow in only one direction are commonplace—consider one-way streets, insect traps, and the staple of the police procedural story, the one-way mirror. However, creating a device that allows waves to pass in only one direction, termed an isolator, is challenging because of the inherently symmetric physics of wave phenomena. On page 516 of this issue, Fleury *et al*. (*1*), taking inspiration from a natural electromagnetic phenomenon, designed and demonstrated an engineered structure that allows one-way transmission of sound waves.

Creating a one-way, or nonreciprocal, structure for general wave flow is more challenging than one might think. The one-way mirror, for example, is not truly a nonreciprocal optical wave device, as the effect is created primarily by a trick of unequal lighting. True nonreciprocity in linear materials is tied to breaking of time-reversal symmetry (*2*). A system exhibits time-reversal symmetry if one solution of the entire system, but run backward in time, is a second solution. This condition is equivalent to interchanging the source and receiver sides of the problem, as illustrated in panel A of the figure. Wave phenomena by their nature generally exhibit time-reversal symmetry (consider how circular ripples on a pond surface can be either outwardly expanding or inwardly converging), so creating a nonreciprocal device or medium takes something special.

Engineering wave propagation nonreciprocity into materials is an area of substantial recent research. There are several different ways to do this, which are summarized in clear and thorough reviews in the context of acoustic (*3*) and electromagnetic (*4*) waves. Interestingly, many efforts that have demonstrated asymmetric power transmission for specific input and output field distributions are not truly nonreciprocal and cannot be used to create general nonreciprocal devices (*3*, *4*). Carefully designed nonlinear structures can exhibit nonreciprocity without time-reversal asymmetry (*3*, *4*), but this approach results in constraints like amplitude dependence that limit its value in wave isolator applications.

It turns out that linear systems that contain a directional bias that is defined by some form of internal motion (a so-called odd vector under time reversal) can be made nonreciprocal (*2*). In such a system, strict time reversal reverses the direction of that internal motion and reverses the bias direction as well. Such systems would be reciprocal if the internal motion, and thus the directional bias, is also reversed when the input and outputs are swapped, in accord with time reversal. Interchanging the input and output ports without reversing the direction of the bias creates a nonreciprocal device by breaking time-reversal symmetry, as illustrated in panel B of the figure.



Obeying and breaking time-reversal symmetry. (**A**) In a material or device without a preferred direction, the fundamentally symmetric behavior of waves means that a solution runs backward in time and is still a solution. This condition is equivalent to interchanging the input and output waves in the system. (**B**) However, if the system contains a flow-based directional bias, and that bias is not flipped when the input and output waves are interchanged, then time-reversal symmetry is broken. Wave transmission through such a system can be dramatically different when the input and outputs are interchanged, and thus nonreciprocal.

Some materials naturally contain this kind of directional bias and are inherently nonreciprocal—for example, the ionized gas of Earth's upper atmosphere permeated by the directional bias of the steady geomagnetic field (*5*). An external magnetic field can also be applied to magnetically active materials, such as ferrites to create nonreciprocity. This approach is used in many practical nonreciprocal optical or radio-frequency isolators (*6*).

In contrast, linear acoustic nonreciprocity had not, until now, been demonstrated except in weak or large-scale forms not suitable for compact applications. Fleury *et al.* have now done precisely that by borrowing the basic physics of the Zeeman effect, in which a biasing magnetic field creates a strongly birefringent medium in which different polarization states interact with different medium resonances. Because this is an effect created by a fixed bias field, such a medium is nonreciprocal. Fleury *et al*. (*1*) create analogous acoustic resonance splitting in a compact circular cell that contains a rotational mean air flow. Counterpropagating acoustic waves in this cell experience different resonant frequencies, an effect that can be derived both from the basics of acoustic wave propagation in a steady mean flow and from a quantum-mechanical operator approach [see the supplementary materials of (*1*)].

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Critically, the mean fluid flow provides the fixed-direction bias field that breaks the time-reversal invariance of the system. The two resonant modes of the system are unequally excited by an input, despite the symmetric port configuration. Careful design, by tuning of the mean fluid flow, enables the interference of these two modes to create a sound null at one of the ports, resulting in complete transmission to the other port.

In this case, the three-port device that was fabricated functions as a circulator, in which an input signal on one port at the design frequency transmits all of its acoustic energy to its neighbor port in the direction of the mean flow, and none to its neighbor port opposite the flow. The resulting nonreciprocity is easily seen: An input signal on port 1 is transmitted fully to port 2, whereas the same input signal on port 2 is fully transmitted to port 3 (not port 1, as would happen in a reciprocal device). A circulator like this can easily be converted into a two-port isolator with a matched termination on one port. The measured sample exhibits an impressive 30 dB of sound isolation in a device built from simple, off-the-shelf components.

A one-way device for sound and vibrations has broad implications. Unidirectional acoustic wave propagation has obvious uses in noise control, acoustic sensors, and manipulation of acoustic scattering. At smaller spatial scales, mechanical vibrations (called phonons in their quantum-mechanical form) are responsible for heat transport in solid materials as well. The work of Fleury *et al*. adds to the bank of ideas that can be applied to manipulating heat flow in a nonreciprocal fashion (although still subject to the laws of thermodynamics) in what is called a thermal diode (*7*, *8*). Challenges in device scaling and bandwidth control remain in applying the mean-flow–based concept demonstrated here to more specific scenarios, but that all-important first step toward general-purpose linear acoustic nonreciprocity has now been taken.

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BOTANY

Pathogen Specialization

The ability to infect new hosts can drive the evolution and specialization of secreted pathogen proteins.

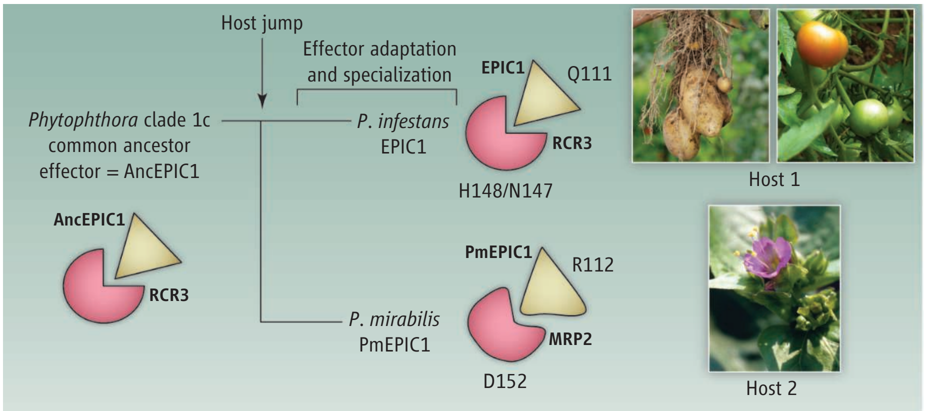
Gitta Coaker

Plants can be attacked by a vast range of pathogen classes, causing substantial agricultural losses. The *Phytophthora* (meaning "plant killer") genus is a particularly destructive pathogen that causes root and stem base decay in a wide range of plants. *Phytophthora infestans*, which precipitated the Irish potato famine, originated in Central Mexico and is closely related to other *Phytophthora* species with distinct host ranges (*1*, *2*). Pathogen effectors that are secreted during infection play a key role in disease biology, but effector-induced adaptation to new hosts is an understudied topic. On page 552 of this issue, Dong *et al.* investigate how *Phytophthora* effector proteins evolve the ability to specialize on new hosts (see the figure) (*3*).

Phytophthora is a genus of oomycetes that exhibit filamentous growth on plants. Oomycetes share some phenotypes with fungi, but are phylogenetically related to photosynthetic brown algae and are thought to have initially emerged from marine environments. The *Phytophthora* genus comprises 10 main lineages designated as clades 1 to 10. Clade 1c, a subdivision of clade 1, includes *P. infestans* (infecting potato and tomato) and *P. mirabilis* (infecting 4 o'clock weeds), indicating that these species share a recent common ancestor (*2*). Genome comparisons between *P. infestans* and *P. mirabilis* highlight alterations and patterns of selection in repetitive DNA containing rapidly evolving families of virulence genes (such as effectors) (*4*).

The 82 effectors undergoing positive selection between *P. infestans* and *P. mirabilis* are promising candidates shaping host specialization (*4*). Dong *et al*. focused their efforts on the EPIC1 effector, which is abundantly secreted during infection of tomato and inhibits extracellular papain-like proteases (including RCR3) that are involved in plant immune perception (*5*).

Dong *et al*. now report that the *P. mirabilis epiC1* ortholog (*PmepiC1*) shows signatures of positive selection, suggesting that this effector has evolved to function in *Mirabilis jalapa*, the 4 o'clock plant, following the split between *P. mirabilis* and *P. infestans*. Using activity-based profiling with a probe that targets papain proteases, the authors demonstrate that recombinant EPIC1 from *P. infestans* effectively inhibits tomato and wild potato RCR3 proteases, whereas PmEPIC1 does not. The authors identify two PmEPIC1 *M. jalapa* targets with homology to RCR3 (MRP1 and MRP2). Subsequent experi-



Route to specialization. A host jump within *Phytophthora* 1c led to the emergence of *P. mirabilis*, which can infect *M. jalapa.* Dong *et al*. show that effector specialization following the host jump is associated with the R112 mutation in PmEPIC1, enabling effective inhibition of the *M. jalapa* MRP2 protease. Polymorphic residues controlling specificity for the host and pathogen are highlighted. Adapted from fig. S18 in (*3*).

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