

PHYSICS

Random Quantum Networks

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The interaction between light and matter at the quantum level offers intriguing ways to process and transport information [see, for example, (1)]. Experimental realizations of quantum computers are, however, still in their infancy. A major challenge is the realization of a qubit—the quantum version of a bit that entangles quantum states—that can be manipulated and coupled to other qubits. For example, one strategy for coupling light and matter places an atom or quantum dot in a tiny cavity, where it couples resonantly with the cavity's optical modes (2). Practical difficulties of this approach arise because a highly efficient cavity is needed, and it must also be exactly tuned to the emission frequency of the source. On page 1352 of this issue, Sapienza *et al.* report an approach that simplifies this problem enormously (3). They have created a photonic structure that intentionally is very disordered, in which efficient random cavities are formed at many frequencies.

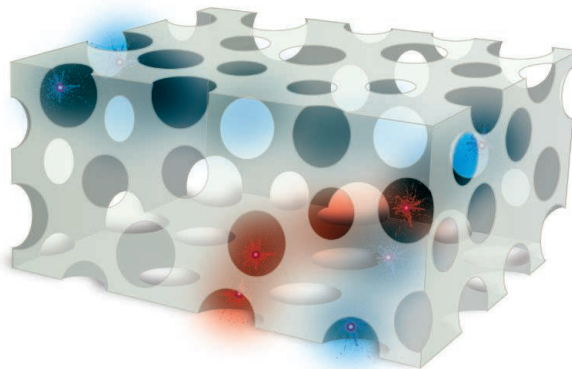
Humans, especially when engineering a mechanism or structure, often favor neat and perfect structures, and often miss the opportunities offered by irregular and disordered systems (4, 5). Biological systems optimize functionality but not necessarily symmetry—the patterns of trees in a forest or cells in our brain are not periodic lattices. Even the highly refined silicon crystals used in electronic devices need the addition of impurities, called dopants, to become useful materials for transistors. In this regard, physicists have tried for years to create clean, periodic photonic crystals (6, 7)—materials that block light over narrow frequency bands. These materials could be used to create high-quality-factor microcavities that can trap light for long periods of time. However, manufacturing problems continue to be encountered that arise from residual disorder in the structure (8).

A very different approach to create photonic materials exploits the fascinating optical properties offered by disorder itself. We might expect that

light becomes incoherent in random structures and would not be able to exhibit interference effects, but this does not occur. The optical response just becomes more complex as the light undergoes multiple scattering events. An example of interference from a disordered photonic material can be observed when coherent laser light is scattered from a translucent material, such as white paper or milk glass. “Speckle,” a grainy pattern of randomly distributed dots, results from the interference of a number of randomly scattered light waves.

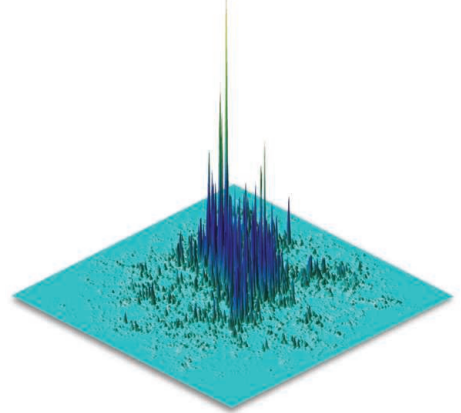
Another powerful example of interference in multiple scattering is Anderson localization of light, which occurs when counterpropagating waves in a random structure interfere constructively to form standing wave patterns (9). These localized modes have a random, irregular spatial profile, but their behavior is similar to that of regular optical cavity modes (see the first figure). It is this principle that Sapienza *et al.* used to create a system in which quantized light sources (in their case, quantum dots) are coupled to optical cavities that are engineered to deviate from a perfect lattice.

To obtain a useful building block for quantum information processing, the atoms or quantum dots must be strongly coupled to a cavity mode (10)—so strongly that the presence of a single photon in the cavity satu-



Random yet robust coupling. Sapienza *et al.* created disordered 1D waveguides to create such modes, but it should be possible to create these modes in a 3D random network of holes. Atoms within this material can couple to these modes, and if the coupling is sufficiently strong, act as single-photon emitters and form quantum networks. Here, two sets of coupled atoms are shown that emit strongly at different frequencies (depicted in red and blue). The localized modes can exchange photons (shown as blue or red light moving between the atoms) and thereby share quantum information.

The optical modes of disordered materials can couple with atomic emission and could create states that would be useful in quantum information processing.



Optical modes spring from disorder. A disordered array of scattering elements can still set up well-defined optical modes, called Anderson-localized modes. Here, a model study shows a localized optical mode created in a two-dimensional planar waveguide containing a random array of holes (12).

rates the excited state of the atom. An excited atom can then repeatedly emit and reabsorb a photon before it has time to escape from the cavity. This process creates an entangled state between the atom and the photon—the photon state is directly connected to the state of the atom. The beauty of this approach is that such an entangled photon can travel to distances far away from the particle, still carrying its quantum information, and couple to other atoms to form a quantum network (11).

In the disordered materials used by Sapienza *et al.*, Anderson-localized modes are formed at random locations and the wave patterns have random central frequencies. Such modes are not formed around a specific defect of the structure, but rather build up over a volume that contains a certain number of scattering elements. The matching of emitters (in this case, quantum dots) and cavities occurs through a statistical process: In certain positions, the emission frequency of a dot matches exactly that of a localized mode, and efficient coupling is obtained.

The dimensionality of the structure plays a crucial role in Anderson localization. The waveguides in the disordered structures used by Sapienza *et al.* create effectively one-dimensional (1D) localized modes. This is the easiest route for obtaining localization, because any nonzero disorder can generate localized modes in the 1D case,

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and the amount of scattering determines only the spatial extent of the modes (and thereby the cavity volume). For 3D structures, like powders or porous networks, light can also be localized, but the amount of scattering has to exceed a certain critical value. Although Sapienza *et al.* did not reach the strong coupling regime, they did see a large effect on the emission of the dots, in the form of a strong emission enhancement. This so-called Purcell effect is a precursor to strong coupling and shows that the strategy is very promising.

The benefits of using disordered materials can be realized both in fabrication and device operation. Disordered structures are much easier and cheaper to make than extremely precise nanoscale cavities. It sounds almost trivial, but disordered structures are robust against disorder. We cannot predict in advance which source will couple to which mode, but the end result will be a broad set of sources in a range of frequencies that are all coupled to cavity modes. For example, it may be possi-

ble to build a single-photon source that is also broadband, meaning that it emits not at just one frequency but over a range of frequencies. The emitters could then be controlled by secondary light beams at frequencies outside the localization band.

The approach of Sapienza *et al.* also raises interesting possibilities in quantum information processing. When Anderson-localized modes occur at the same or nearby frequencies, they can couple to each other to form so-called necklace states. A series of localized modes can exchange photons and thereby share the quantum information of the atoms or dots located in each mode. It might be much simpler to construct a large-size quantum memory or information processor this way than with perfect, periodic coupled nanocavities (see the second figure). The information contained in such a random structure can be written, read, and erased by external light beams that are also multiply scattered, but not localized, and carry within their speckle pat-

tern the information stored in the quantum network. This is but one of many possibilities that may arise from the use of disordered photonic structures.

References and Notes

1. M. A. Nielsen, I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge Univ. Press, Cambridge, UK, 2000).
2. T. Wilk, S. C. Webster, A. Kuhn, G. Rempe, *Science* **317**, 488 (2007).
3. L. Sapienza *et al.*, *Science* **327**, 1352 (2010).
4. For an inspiring alternative view on beauty, see (5).
5. T. Itoh, *Wabi Sabi Suki: The Essence of Japanese Beauty* (Mazda Motor Corporation, Hiroshima, 1993).
6. J. D. Joannopoulos, R. D. Meade, J. N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton Univ. Press, Princeton, NJ, 1995).
7. K. Sakoda, *Optical Properties of Photonic Crystals* (Springer-Verlag, Berlin, 2001).
8. A. F. Koenderink *et al.*, *Phys. Rev. B* **72**, 153102 (2005).
9. A. Lagendijk, B. van Tiggelen, D. S. Wiersma, *Phys. Today* **62**, 24 (2009).
10. D. P. DiVincenzo, *Fortschr. Phys.* **48**, 771 (2000).
11. H. J. Kimble, *Nature* **453**, 1023 (2008).
12. D. S. Wiersma, *Nat. Phys.* **4**, 359 (2008).

10.1126/science.1187084

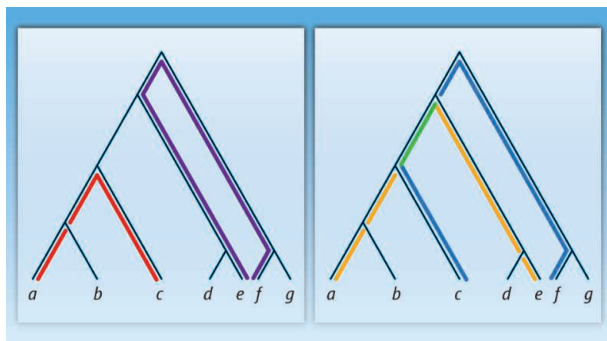
EVOLUTION

Trees, Fast and Accurate

Elizabeth S. Allman and John A. Rhodes

Inferring evolutionary relationships from DNA or protein sequence data is now routine in biological investigations. Although techniques have improved for using such information to generate phylogenetic trees that represent these histories (1), challenges remain. In particular, the computational demands of preferred statistical approaches make them infeasible for finding large phylogenies. However, on page 1376 of this issue (2), Roch theorizes that a less comprehensive analysis might be surprisingly reliable.

For a moderate number of taxa, the now-dominant methods adopt a probabilistic model of sequence evolution and then, using either maximum likelihood (ML) or Bayesian frameworks, determine the trees that best fit the sequence data. Such analyses are well grounded in statistical tradition and, if the model approximates reality, can be expected



to perform well. However, they are computationally intensive: ML leads to a complex optimization problem not only over many numerical parameters, but also over all trees that might relate the taxa. Bayesian approaches involve a random walk over these trees. For n taxa there are $1 \cdot 3 \cdot 5 \cdot \dots \cdot (2n - 5)$ trees to be considered, so that when n is large, the size of tree space is a fundamental impediment. This explosion in the number of trees results in unacceptably long run times of computer analyses, so searches for optimal trees may be incomplete.

An alternative faster approach is to algorithmically construct a single tree by successively grouping closely related taxa. The

A scalable and fast method for building very large evolutionary trees achieves greater accuracy than previously thought.

Distance estimates. Shown is an example of a "true" phylogenetic tree representing the evolutionary history of seven taxa (*a*, *b*, *c*, *d*, *e*, *f*, and *g*). Pairwise distances between taxa are computed from orthologous gene sequences. Distances are random variables reflecting path lengths in the tree. **(Left)** The paths between *a* and *c* (red) and between *e* and *f* (purple) do not share a common history, so the random variables [distances $d(a, c)$ and $d(e, f)$] are independent of each other. **(Right)** The paths between *a* and *e* and between *c* and *f* share a common history (green), so independence is lost; $d(a, e)$ (yellow and green) and $d(c, f)$ (blue and green) are correlated.

sequences for each pair of taxa *a*, *b* are compared, and a single number $d(a, b)$ is computed to express their distance (relationship) along the unknown tree. The sequences are then discarded, as all decisions on joining taxa are based solely on these distances. Two well-known examples of such agglomerative algorithms are the unweighted pair group method with arithmetic mean and the more reliable neighbor-joining (NJ) method.

The apparent drawback of distance-based techniques lies in only comparing sequences pairwise—the full information that could be extracted from n -way comparisons is not used. Thus, distance methods do not perform as well as more complete statistical

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