phase gradient image can be obtained. The utilization of low spatial coherence not only reduces speckle noise, it also increases the lateral resolution. This is because the phase gradient image obtained with low spatial coherence is identical to the result of coherent synthetic aperture microscopy. This implies the possibility of tomographic imaging using axial scanning[10].

By integrating phase gradients, the work by Kwon and colleagues can be readily extended to QPI. However, this requires a carefully designed shearing distance — if the displacement is too small compared with the diffraction limit, the image will lose contrast, resulting in a low signal-to-noise ratio. By contrast, if the displacement is greater than the diffraction limit, fine features of the sample will be lost. Another issue is optical aberration. The current design exhibits elongation in point spread functions (PSFs) as the focal point locates away from the centre. The elongated PSF results in a varying signal-to-noise ratio depending on the position because of the mismatch between PSFs and the shearing distance. Nevertheless, optical aberration can be mitigated by adding metasurfaces or performing numerical compensation once a quantitative phase image is obtained.

The work by Kwon and colleagues suggests the possibility of miniaturizing various imaging techniques down to a single-layer device. This type of miniaturization is expected to bridge different techniques and to facilitate new applications. For example, metasurface devices can pave the way for point-of-care applications by providing a simple diagnostic platform, particularly when combined with machine-learning algorithms[11]. In the future, it will be exciting to witness the emergence of metasurface devices as integrative solutions for microscopic imaging and biomedical studies. ❐

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Published online: 29 January 2020
https://doi.org/10.1038/s41566-019-0552-x

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LOCALIZATION DYNAMICS

# Optical circuits cross dimensions

Accessing the physics of higher-than-three-dimensional systems is naturally challenging. Researchers have now demonstrated that light dynamics in a one-dimensional array of carefully arranged photonic waveguides mimics the time evolution of particles in high-dimensional lattices.

Alberto Amo and Oded Zilberberg

The dimensionality of a system crucially determines the way particles can move within it. Being terrestrial, we are commonly used to moving on the two-dimensional surface of Earth. Meeting other people along the way, we can pass around them by navigating sideways. We are, of course, also mindful to the three-dimensional volume around us, for example, by sensing the profile of the Earth's surface while walking up and down hills, or by jumping over obstacles. Similarly, we are familiar from our daily life with lower one-dimensional dynamics when standing in a queue.

Clearly, we can grasp how the dimensionality of a system impacts our three-dimensional daily lives. Mathematically, however, we can always ponder the impact of dimensionality in dimensions higher than three. Interestingly, stretching our imagination to such higher dimensions allows us to obtain a deeper understanding of observed physical phenomena. In cosmology, for example, researchers are looking into the curvature of our Universe inside the four-dimensional space-time volume, thus endeavouring to answer fundamental questions about its expansion. Similarly, string theory relies on higher-dimensional models for attempting to describe all natural forces in a single unified model. Turning to particle motion in materials, we can identify exotic localization signatures and transport properties that are unique to such higher-dimensional materials, for example, in topological systems that exist in arbitrary dimensions.

Technological advances now enable us to emulate higher-dimensional transport properties within our three-dimensional world. The dynamics of particles in a lattice of any dimension is directly connected to a cubic graph problem (Fig. 1a–d). The sites of the lattice form the vertices of the graph and the hopping of particles between sites are the links[1]. It is quite straightforward to see that in a simple one-dimensional lattice each vertex has two links, one to each of its nearest neighbours. In a two-dimensional square lattice, each vertex maintains four links forming a square, and in a three-dimensional cubic lattice, each vertex has six. In short, each additional dimension adds two more links to each site, see, for example, Fig. 1a. A variety of approaches have been proposed to realize such higher-dimensional connectivity and ensuing dynamics using 'synthetic dimensions', for example, using parametric coupling between internal degrees of freedom[2,3], through dynamical modulation of superlattice potentials[4,5], and in quasiperiodic structures[6].

Now, writing in *Nature Photonics*, Lukas Maczewsky and co-workers propose a new approach[7]. They have shown experimentally that the dynamics of a particle in a given site of a high-dimensional lattice (in principle, of any dimension) can be mapped onto the

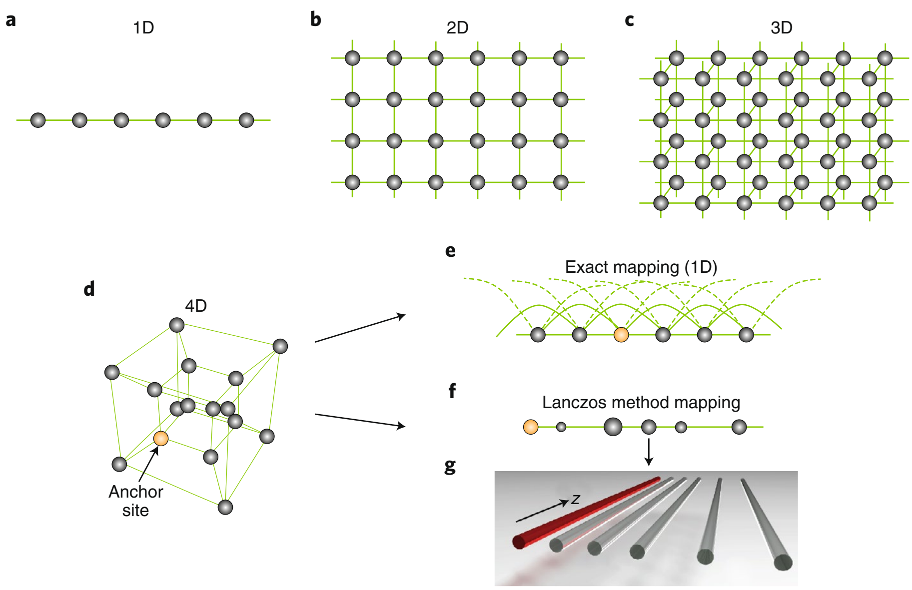


**Fig. 1 | Mapping high-dimensional structures onto a one-dimensional lattice. a–c**, Lattice networks of dimensionality one to three with nearest-neighbour connections. **d**, Sketch of a hypercube unit cell of a four-dimensional cubic lattice. **e**, Any high-dimensional lattice can be exactly mapped onto a one-dimensional array as long as all the connections between the nodes are kept. **f**, The Lanczos method reduces a high-dimensional lattice to a one-dimensional one, where only the anchor site in the reduced lattice (orange point) follows the same dynamics as the selected anchor site in the high-dimensional lattice. **g**, Array of coupled waveguides implementing the reduced one-dimensional lattice, in which photons propagate in the *z* direction. The photon dynamics at the first site follows that of the anchor site. Panel **g** reproduced with permission from ref. [7], Springer Nature Ltd.

dynamics of photons in a waveguide in a simple one-dimensional photonic lattice.

Naively, one can align all the high-dimensional lattice points on a line, as long as we keep track of all the links between sites, which implies that the equivalent one-dimensional lattice will have an intricate pattern of nearest and long-range hoppings (Fig. 1e). Such a solution is very hard to implement in an actual physical system. To solve this issue a number of proposals based on transformation techniques have been put forward[1,8,9]. The goal of the transformation is to preserve specific properties of the initial system while reducing its complexity. A remarkable example involves supersymmetry transformations, which were originally developed in high-energy physics to provide a unified description of bosonic and fermionic particles. More recently, supersymmetry has been employed to design different photonic metamaterials with identical scattering properties[8], and superpartner lattices with the exact same spectrum as the original lattice except for the ground state (which is removed)[9]. Using similar techniques it has been shown that, indeed, a three-dimensional lattice can be mapped onto a one-dimensional array of photonic resonators of waveguides with simple nearest-neighbour hopping with the same spectrum as the original lattice[1].

While these methods provide a recipe to design a low-dimensional photonic lattice with the exact same eigenmode spectrum of a complex high-dimensional one, they do not deliver much information about the photon dynamics in the higher-dimensional lattice. Accessing these dynamics is crucial for understanding, for instance, the effect of different types of disorder in high dimensions. Maczewsky and collaborators have revisited a linear algebra algorithm, dubbed the Lanczos method, known since the 1950s, to develop an alternative way of mapping an *N*-dimensional network onto a one-dimensional lattice with nearest-neighbour couplings (Fig. 1f). The price to pay with this method is that the transformation mixes all sites of the higher-dimensional network except for one, called the 'anchor' site. And here is where interesting things happen: the dynamics of particles in this specific site of the higher-dimensional network is identical to the dynamics of the first site of the equivalent one-dimensional lattice. In their work, Maczewsky and colleagues experimentally demonstrate this mapping using photonic lattices of coupled waveguides inscribed in fused silica (Fig. 1g). They fabricate one-dimensional lattices that account for the dynamics of an anchor site of a network of up to seven dimensions.

What is this useful for? Though the study of the dynamics is restricted to a single site, it provides plenty of valuable information on the original high-dimensional lattice. For instance, by studying the escape time of photons from the anchor site, Maczewsky and co-workers reveal a new kind of localization transition that takes place solely in four dimensions and above. A different area in which this technique would be beneficial is topological physics. So far, most of the explored topological phenomena correspond to real materials in our three-dimensional world. In this class of materials, a property of the bulk, the topological invariant, determines the existence and dispersion of various states present at the boundaries of the system. For instance, in a two-dimensional Chern insulator, chiral edge states appear. Would it be possible to design a higher-dimensional topological system and sample its boundary dynamics using this method? Can the crucial impact of disorder on such systems be explored under the same mapping? Does the map also imply correlation dynamics such as boson sampling in higher-dimensional systems? Although the answers to these questions are not yet clear, the mapping method developed by Maczewsky and co-workers opens up a variety of opportunities to peek at new phenomena from high dimensions. ❐

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Published online: 29 January 2020
https://doi.org/10.1038/s41566-019-0578-0

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