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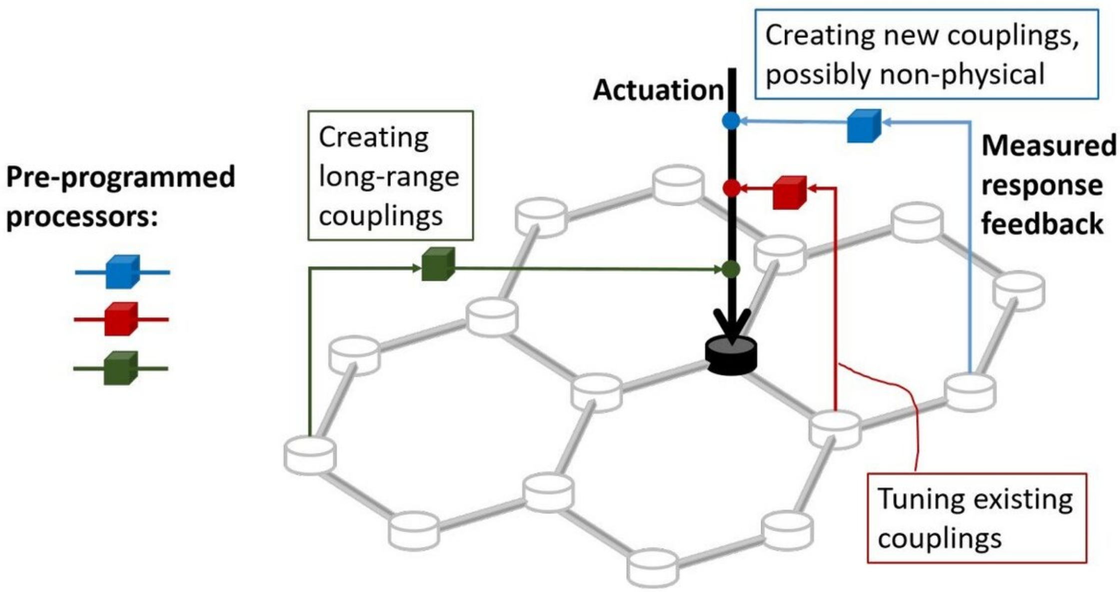
Topological mechanical metamaterials go beyond Newton's third law

November 19 2020, by Anna Demming



An active feedback controlled metamaterial. Whereas usually couplings between metamaterial elements are fixed, incorporating pre-programmed controllers can enable non-Newtonian mechanical interactions. Credit: Lea Sirota

A change in perspective can work wonders. This has been especially true with respect to the paradigms for explaining material properties using the concept of topology, "ideas that are currently revolutionizing condensed matter physics," according to Tel Aviv University researcher Roni Ilan. While topological physics first emerged in condensed matter physics, the ideas have now spread into many other areas, including optics and photonics, as well as acoustics and other mechanical systems, where things have been getting a little tricky.

Although mechanical wave systems can offer valuable insights into the workings of quantum systems, including topological phenomena, researchers taking this approach had hit a wall with Newton's third law of motion, which rules that every action must result in an equal and opposite reaction. Some quantum systems simply don't abide by this kind of reciprocity, making them difficult to emulate in mechanical systems. However, collaborators at Israel's Tel Aviv University have now found a way to mimic non-Newtonian behavior in mechanical systems, and thereby develop a mechanical implementation for some of the more intractable topological quantum systems, which may offer fundamentally new insights into both the mechanical and quantum topological systems.

The team brought together expertise from several different fields—Ilan's in condensed matter theory, Yair Shokef's in soft matter, Yoav Lahini's specialist knowledge in topological photonics, and the missing link that unified the work, Lea Sirota's background in mechanical engineering and control theory. "Somehow, we all converged when Lea came here and started talking about these things," says Lahini.

Breaking symmetries

The complications that crop up when trying to design mechanical analogs of quantum systems essentially stem from symmetry breaking. In spatial terms, this might mean that interactions between components in the systems act differently in different directions, such as those at the heart of quantum spin Hall and quantum valley Hall effects in 2-D systems. However, mimicking these effects in mechanical systems is not such an issue because you can easily play with geometry. Symmetry breaking in time gets more complicated.

At the microscopic level, mechanics is time reversible. Consider a movie of two particles moving toward each other, colliding and rebounding—play it backwards, and you still get a physically credible movie of two particles moving toward each other, colliding and rebounding. However, the quantum effects that arise when objects interact with magnetic fields, for example, break this time symmetry—play the movie backward, and something in the picture does not add up. Mimicking these effects means introducing some kind of non-reciprocity so that there is no longer an equal and opposite reaction to every action, and that is something that mechanical systems just don't do.

"People circumvented this barrier using somewhat involved realizations, for instance, introducing rotating flows or rotating gyroscopes and other complexities that would eventually mimic spins in quantum systems," explains Shokef. The problem here is that adding gyroscopes or whatever to something that is not spinning adds degrees of freedom that are not present in the system you are trying to mimic. So while the system might start to respond like a non-reciprocal quantum state in some ways, it's hard to avoid unwanted additional effects from these auxiliary degrees of freedom. Here, Sirota's expertise in control theory had huge advantages.

Virtual interactions

As Sirota explains, control theory is a field in mechanical engineering that uses mathematical tools to devise algorithms that describe a system's behavior in response to some kind of force or actuation. It allows the kind of interventions that are found in autonomous or assisted cars. For instance, while traditionally, a plastic bumper at the front of the car would absorb the impact of a collision, in an autonomous or assisted vehicle, a camera measures the distance to the car in front and intervenes with brake control when it gets too close. As Shokef points out, this is already mimicking a non-reciprocal interaction because there is no equal and opposite reaction in the car in front as there would be from a collision with the bumper. Consequently, the researchers were able to apply principles from control theory to design an active mechanical metamaterial capable of similar non-reciprocity in the interactions between elements.

They began by modeling a mechanical metamaterial made up of an array of connected mass units, where the units can move only up or down—one degree of freedom per mass. However instead of having the dynamics of the system ruled by Newton's laws of motion, a feedback controller is situated over each mass, which measures the position of neighboring masses, calculates how the mass would respond if governed by some quantum non-reciprocal expression for the interaction, and then applies just the right actuation to get that response. "We replace the natural interaction (of springs) with a virtual interaction if you like," says Lahini.

Simulations of the active-feedback-controlled mechanical metamaterial showed that it could mimic the quantum Haldane model, which describes the quantum Hall effect in the absence of a magnetic field, something that had been a struggle to mimic using passive mechanical elements. What's more, it does so "with no spinning parts," as Sirota emphasizes, adding, "You can mimic different topological effects on the same platform." The researchers were also able to mimic the modified Haldane model, as well as a pseudospin multipole topological insulator by simply adjusting the control software.

While there has been some success in realizing active mechanical metamaterials in one dimension, this work breaks new ground for two-dimensional mechanical metamaterials with active control feedback. Next, Sirota is working on a realization of the metamaterial using acoustic waves, which are easier to control and may offer intuitive insights into quantum mechanics. Here, an acoustic wave passes between two parallel plates where one comprises the active feedback control elements using speakers and microphones to impart virtual non-reciprocal interactions.

As well as practical capabilities, the system may, for instance, offer sound isolation and acoustic cloaking; the researchers see the potential for their mechanical analog to add to the understanding of topological states of matter. "If things map exactly one-to-one, it's not interesting," says Shokef. "But the moment this mapping is not perfect, new and interesting phenomena come up."

"Moreover," Lahini adds, "The mechanical system can allow to controllably introduce many components that are hard or impossible to achieve in condensed matter—interactions, nonlinearities, dynamic potentials, boundaries and more."

More information: Sirota et al., Non-Newtonian topological mechanical metamaterials using feedback control. *Physical Review Letters* (2020). journals.aps.org/prl/abstract/ … ysRevLett.125.256802

Sirota et al., Non-Newtonian topological mechanical metamaterials using feedback control. arXiv:2002.10607 [cond-mat.mes-hall]. arxiv.org/abs/2002.10607