Appreciating the classical elegance of time crystals

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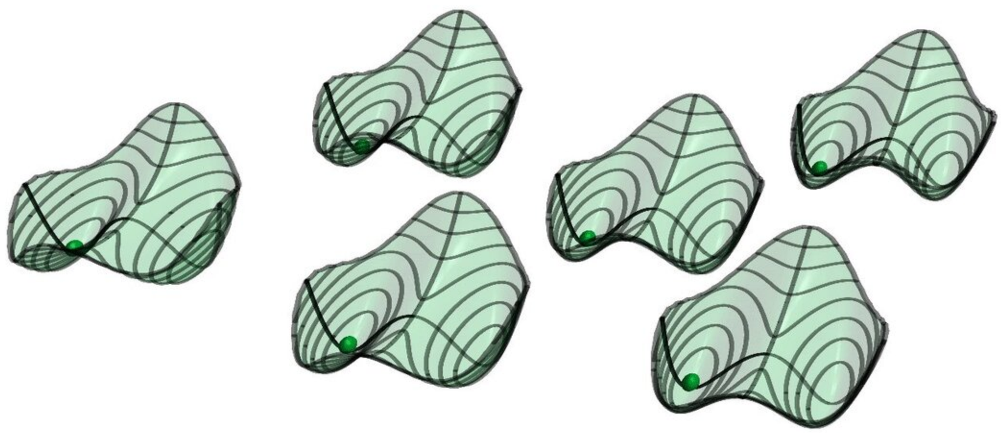


Quasi potentials of six parametric oscillators with weak all-to-all coupling. Stable solutions are located at the minima. The balls indicate the symmetric solution, where all oscillators are in phase.(Screenshot from accompanying animation) Credit: ETH Zurich/D-PHYS Toni Heugel

Structures known as time crystals, which repeat in time the way conventional crystals repeat in space, have recently captured the interest and imagination of researchers across disciplines. The concept has emerged from the context of quantum many-body systems, but ETH physicists have now developed a versatile framework that clarifies connections to classical works dating back nearly two centuries, thus providing a unifying platform to explore seemingly dissimilar phenomena.

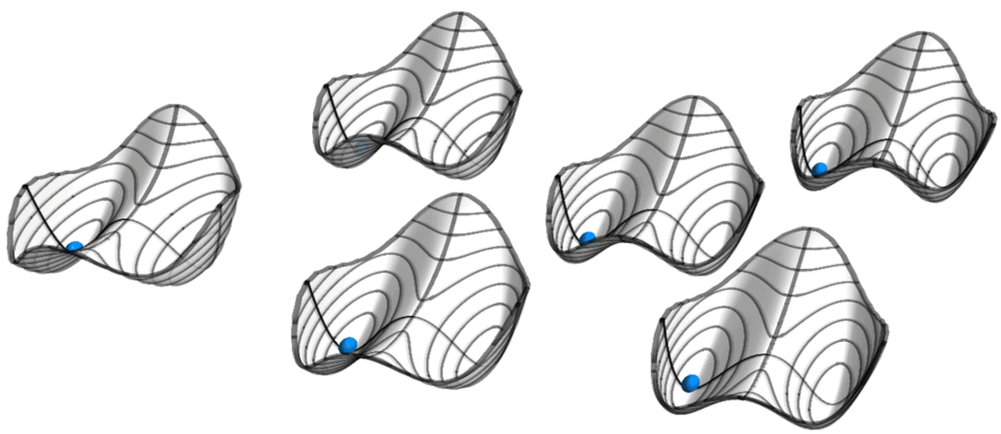
In a crystal, atoms are highly ordered, occupying well-defined locations that form spatial patterns. Seven years ago, the 2004 Physics Nobel laureate Frank Wilczek pondered the possibility of a time analogue of crystalline spatial order—systems that display sustained periodic temporal modulations in their lowest-energy state. The concept of such structures with an oscillating ground state is highly intriguing. Alas, not long after the idea was published, it was proven that such time crystals are not possible without breaking fundamental laws of physics. However, subsequent theory work suggested that when quantum many-body systems are periodically driven, new persistent time correlations emerge that are evocative of Wilczek's time crystals. These driven systems were dubbed discrete time crystals, and in 2017, the first experimental realizations of such states were reported in ensembles of coupled particles (ions, electrons and nuclei) that display quantum-mechanical properties.

A not-so-brief history of time crystals

Before long, astute observers spotted distinct similarities between discrete time crystals in quantum systems and so-called parametric resonators, a concept in classical physics reaching back to work by Michael Faraday in 1831. The connection between these two bodies of work remained, however, opaque. Now, theorists have developed a new framework goes a long way toward lifting the ambiguities surrounding the similarities between periodically driven classical and quantum systems.

Writing in an article published today in the journal *Physical Review*

Letters, Toni Heugel, a Ph.D. student in the Department of Physics at ETH Zurich, and Matthias Oscity, a student at the same institution, working with Dr. Ramasubramanian Chitra and Prof. Oded Zilberberg from the Institute for Theoretical Physics and with Dr. Alexander Eichler from the Laboratory for Solid State Physics, report theoretical and experimental work that establishes how discrete time crystals can be generated that, on the one hand, require no quantum mechanical effects and, on the other hand, display genuine many-body effects, which is a characteristic of discrete time crystals reported in quantum systems.



Quasi potentials of six parametric oscillators with weak all-to-all coupling. Stable solutions are located at the minima. The balls indicate the symmetric solution, where all oscillators are in phase. The Hamiltonian H govern the motion of the system has period T, while the solution itself has period 2T. This discrete time translation symmetry breaking makes the system a discrete time crystal. Credit: ETH Zurich/D-PHYS Toni Heugel

Many ways to subharmonic frequencies

There is one obvious similarity between classical parametric resonators and experimentally realized discrete time crystals in quantum many-body systems: Both display emergent dynamics at frequencies that are fractions of the drive frequency. In the context of discrete time crystals, the emergence of oscillations at such subharmonic frequencies breaks the temporal periodicity of the driven system, providing a 'time analogue' to crystalline spatial order, in which the symmetry of space is broken. In classical parametrically driven systems, subharmonic frequencies appear in more familiar ways: A child on a swing, for instance, modifies the centre of gravity at twice the frequency of the resulting oscillation, or the ponytail of a runner oscillates at half the frequency of the vertical head movement.

But do these dissimilar phenomena have anything to do with one another? Yes, say the ETH physicists. In particular, they pinpoint where many-body aspects appear in classical systems. To do so, they considered classical nonlinear oscillators with tunable coupling between them.

Unifying framework for periodically driven classical and quantum systems

It is well known that for certain driving frequencies and strengths, parametric oscillators become unstable and then undergo a so-called period-doubling bifurcation, beyond which they oscillate at half their driving frequency. Heugel, Oscity and their colleagues explore what happens as several such oscillators are coupled together. In calculations as well as in experiments using two strings with variable coupling between them, they find two distinct regimes. When the coupling is strong, the two-string system moves collectively, recreating in essence the movements of the child on a swing or the ponytail of a runner. However, in the case of weak coupling between the strings, the dynamics of each string are similar to those displayed by the uncoupled system. As a consequence, the coupled oscillators do not bifurcate collectively but bifurcate individually at slightly different parameters of the drive, leading to richer overall dynamics, which grow ever more complex as the systems get larger.

The ETH researchers argue that such weakly coupled modes are similar to the ones that emerge in quantum many-body systems, implying that their framework might explain the behaviors seen experimentally in these systems. Moreover, the new work prescribes general conditions for generating classical many-body time crystals. These could ultimately be used to both interpret and explore features of their quantum counterparts.

Taken together, these findings therefore provide a powerful unifying framework for periodically driven classical and quantum systems displaying dynamics at emergent subharmonic frequencies—systems that have been so far described in very different contexts, but might be not that dissimilar after all.

More information: Toni L. Heugel et al, Classical Many-Body Time Crystals, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.123.124301

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