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Non-equilibrium quantum matter on demand

The quest for a theory of nonequilibrium dynamics was once compared by John von Neumann to the problem of describing a theory of nonelephants. He was alluding to the fact that thermal equilibrium allows for the unification of seemingly diverse systems but non-equilibrium opens up a plethora of different non-universal phenomena. In recent years addressing this challenge has increasingly moved into the center of quantum many-body and condensed matter research. In this colloquium, we focus on the non-equilibrium dynamics of quantum materials interacting with light in a way that allows to engineer their properties in a desired fashion. The idea of non-equilibrium engineering can be illustrated by the Kapitza pendulum, for which a fast oscillation of the pendulum's pivot point leads to an instability of the stable equilibrium and a dynamical stabilization of the unstable upright position.The Kapitza class of phenomena are now coined Floquet engineering: the design of effective Hamiltonians for slow degrees of freedom by fast periodic driving. Floquet engineering with lasers has found applications in atomic and molecular physics and has inspired control by shaking of cold atoms in optical lattices. In materials, by contrast, observations that can be characterized as non-equilibrium engineering are still relatively scarce and often not in the Floquet regime. One route to alter material properties on ultra-fast time scales beyond Floquet engineering is to target meta-stables which are hidden from thermal pathways. Another way is to employ non-linear phononics, which has recently lead to time dependent control of superconducting phases of matter using light. We will review all these novel avenues of ultra-fast materials engineering in this colloquium.