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The unexpected duality of gravitational and condensed-matter physics

Holographic Quantum Matter

Sean A. Hartnoll, Andrew Lucas, and Subir Sachdev
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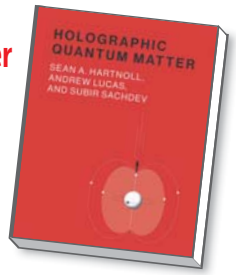

High-energy and condensed-matter physicists have long enjoyed a fruitful interchange of ideas and techniques. The microscopic laws that govern elementary particles share a surprising number of similarities with the collective behavior of matter at macroscopic scales. For example, the standard model of particle physics relies heavily on the notion of spontaneously broken global and local symmetries, concepts that have their roots in the observed behavior of ferromagnets and superconductors.

A relatively new example of the continuing dialog between the two fields is holographic quantum matter, a subject physicists have been vigorously pursuing for more than a decade. Developments originating in superstring theory have led to the remarkable realization that strongly interacting quantum matter can be modeled in terms of gravitational physics in one higher dimension and that gravitational physics can also be modeled as quantum matter. That approach is variously referred to as gauge/gravity duality, holography, holographic duality, or the anti–de Sitter/conformal field theory correspondence, and there is by now a vast literature on the subject. *Holographic Quantum Matter*, a new book by Sean Hartnoll, Andrew Lucas, and Subir Sachdev, gives an excellent conceptual overview of the field while providing enough technical detail for the reader to perform relevant computations.

A few key ideas that underlie holographic duality are useful to keep in mind to appreciate the scope and limitations of that approach. First of all, we have the large-N approximation. Since the 1970s physicists have known that strongly interacting quantum systems can simplify drastically if the number of degrees of freedom is taken to be large. Indeed, the theory becomes effectively classical when expressed in terms of the appropriate collective variables. Remarkably, under the right circumstances this collective description includes gravity in one higher dimension. Hence classical general relativity, cou-

pled to matter fields of various types, emerges out of strongly interacting quantum matter.

If the gravitational theory is sufficiently simple—that is, accurately governed by a Lagrangian with a small number of fields and interactions—holographic duality becomes useful. The emergence of a new holographic spatial dimension leads to physics at different scales in the original system being projected to physics at different locations in the holographic direction.

Next, entropy generation and dissipation are key concepts governing the out-of-equilibrium dynamics of interacting matter. Thermal systems are mapped by the duality to black holes, whose thermal nature is due to Hawking radiation. Entropy generation arises when matter falls through the black hole horizon, a process readily described by solving, often numerically, systems of differential equations.

Finally, the physics of ordinary metals can be formulated in terms of quasiparticles and the associated Landau–Fermi liquid paradigm. Physicists have a strong understanding of the thermodynamic and transport properties of such systems, but there is intense interest in materials that fall outside that paradigm. When no quasiparticles are present, the physics is instead governed by a quantum critical soup of gapless degrees of freedom. Traditional quasiparticle-based tools are ineffective in that context, but holographic duality maps those systems to classical field theory modes, yielding a description that is tractable analytically.

The authors of *Holographic Quantum Matter* systematically develop all these fundamental ideas along with their applications to thermodynamic and transport phenomena, both near and far from equilibrium. Some connection is made to experiments in systems such as cuprate superconductors, graphene, and heavy fermion compounds. To properly absorb the material, the reader should be comfortable with general relativity and quantum field theory and should have broad familiarity with condensed-matter physics, although some topics could be learned on the fly as needed. The reader should come away appreciating that holographic duality provides a novel class of solvable models for strongly interacting quantum matter. However, holographic duality is best viewed as a way of placing certain universal phenomena in a tractable framework. It is not reasonable to expect a specific gravitational model to accurately describe in full detail a specific physical system of interest.

The authors are exceptionally well qualified to review the given subject; they are responsible for many of the developments discussed in this review. The prose is clear and authoritative throughout. I appreciated the efforts the authors made to identify unifying themes rather than simply describing one model after another. The extensive list of references will be very helpful for the reader who wishes to delve deeper. Each chapter contains a collection of well-thought-out problems taken from the literature. I recommend *Holographic Quantum Matter* without question to anyone who wishes to pursue research at the interface of condensed-matter and high-energy physics or to anyone interested in a broad overview of an active and fruitful field.

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