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A note on compacted networks

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fit better to power-law dependences on energy than to conventional fits.

All of those symptoms were explained without the use of arbitrary free parameters in the final papers of a long sequence dating back to 2004, by me and by Philip Casey and me,[4] while the AdS/CFT literature holds nothing resembling a connection back to the parameters of the real solids, nor any discussion of the other anomalies. I believe that our theories are exact, in the sense of continuation, in a considerable region of the phase diagram.

Incidentally, the phase diagram of the real cuprates is only vaguely similar to the conventional diagram shown in Liu's figure. For instance, the strange metal shows no evidence of terminating on the right in a true Fermi liquid.

It is amusing that the methods we use *are* closely related to results in quantum field theory, but to discoveries of three decades or more ago about "anomalies" such as the well-known chiral anomaly of Roman Jackiw and Claudio Rebbi. At about the same period, we condensed-matter theorists were concerned with what we called "x-ray edge anomalies," but we did not realize they were related to our colleagues' anomalies.

As a very general problem with the AdS/CFT approach in condensed-matter theory, we can point to those telltale initials "CFT"—conformal field theory. Condensed-matter problems are, in general, neither relativistic nor conformal. Near a quantum critical point, both time and space may be scaling, but even there we still have a preferred coordinate system and, usually, a lattice. There is some evidence of other linear-T phases to the left of the strange metal about which they are welcome to speculate, but again in this case the condensed-matter problem is overdetermined by experimental facts.

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■ **Liu replies:** While many ingenious ideas have been advanced to explain the strange-metal phase, the community has not reached a consensus, and many of the phase's properties remain mysterious. Philip W. Anderson's hidden Fermi liquid theory, arguably a most ambitious attempt, has provided a useful lens to view various aspects of the phase, but further developments are worthwhile.

As described in my Quick Study, a key obstacle in the pursuit to explain the strange metal phase is the lack of a suitable mathematical framework to characterize "quantum soups"—strongly interacting, dense quantum matter whose constituents have lost their individuality. Holographic duality has now provided such a framework, although only for the class of systems that have gravity duals. It does for those quantum soups what Boltzmann equations do for a dilute gas of quasiparticles: It enables one to calculate reliably all equilibrium and nonequilibrium properties.

At short distances, holographic systems are conformal, Lorentz invariant, and often supersymmetric, all of which make them seem poor models for real-life condensed-matter systems. Those symmetries, however, are all destroyed at long distances if a temperature or a chemical potential is turned on. The surprise of the past few years is that despite significant differences in short-distance details, at long distances most states of matter that have been understood—superfluids, Fermi liquids, magnets, stripes, and so on—can be described in terms of dual gravity systems. Such insensitivity to microscopic detail gives hope that the striking parallels in macroscopic behavior found between black holes and strange metals are not accidents, and gravity may help us decipher the mysteries of strange metals.

I thank Anderson for emphasizing other anomalies exhibited by the strange-metal phase of cuprates that I did not have space to mention. He is correct that the holographic approach has not yet produced a model that could account for all anomalous properties. However, the power-law dependence of photoemission spectra on energy, his last bullet point, is a hallmark of holographic strange metals. I discussed that point in the last part of the Quick Study, in terms of the power-law temperature dependence of scattering rates. Such power laws follow from the semilocal property emphasized in the second-to-last paragraph.

Whether or not one finds a "conventional" explanation for strange metals, connections between the physics of strange metals and black holes are worth exploring. They hint at a new paradigm for thinking about strongly correlated quantum soups. As an added bonus, we may also obtain new insights into quantum gravity from advances in condensed-matter physics.

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Edmund Stoner and the Bohr atom

The 100th anniversary of the Bohr atom this year is an opportune time to call attention to a little known paper that Edmund Stoner, then a student of Ernest Rutherford and Ralph Fowler at Cambridge University, wrote in 1924. Called "The distribution of electrons among atomic levels,"[1] it was the first paper to give a correct formulation of the Bohr atom for many electrons.

In Arnold Sommerfeld's preface to the fourth edition of his *Atomic Structure and Spectral Lines*, the author gave special mention to *einen grossen Fortschritt* (a great advancement) brought about by Stoner's analysis. As a result, Stoner's paper came to the attention of Wolfgang Pauli and was of great value to his formulation of the exclusion principle in quantum physics.[2] Subsequently, Stoner applied the exclusion principle to calculate the maximum mass of white dwarfs a year before Subrahmanyan Chandrasekhar, who generally is given credit for the discovery (reference 3; see also PHYSICS TODAY, July 2011, page 8).

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A note on compacted networks

In their cover article "Networks in motion" (PHYSICS TODAY, April 2012, page 43), Adilson Motter and Réka Albert present an interesting gallery of networks (their figure 1) comprising human brains, social networks, and internet service providers. Their gallery provides much food for thought for mathematicians and physicists interested in percolative structures. Many of the factors controlling the percolative expansion of networks and their possible phase transitions remain unknown and are an active area of research.

Compacted networks, a very important class of classical percolative networks, are not mentioned in the Motter and Albert article. Compacted networks are all around us, the most often overlooked example being window glass. They are self-organized by short-range connectivity rules (which can also be found in Motter and Albert's examples), but in addition they have been compacted by long-range forces, seldom if ever discussed in models. In the window glass example, valence-bond rules govern short-range connectivity, but there are also long-range van der Waals forces that cause the glass density to be usually only about 10% lower than related crystalline densities.

The behavior of many physical systems is governed by delicate balances between short- and long-range forces, so the existence of compacted networks will not come as a surprise to most readers of PHYSICS TODAY. What may come as a surprise is that quantitative theories of compacted networks are already being used by industry to design new specialty glasses, like extraordinarily damage-resistant Gorilla glass.[1]

Self-organized percolation appears in many contexts. For instance, combined charge and rigidity percolation explains many features of high-temperature superconductors, including limits on the transition temperature.[2] In the biosciences, the classical compacted globular structures of protein folds are determined by the competition between hydrophobic and hydrophilic forces. A new theory explains evolutionary trends of influenza virus in terms of those forces.[3] Based on ideas of self-organized criticality[4] and derived from a bioinformatic study[5] of self-similarities in 5526 segments from the Protein Data Bank, it successfully predicts the frequency of disease mutations and may have important applications for the use of mutation-prolific viruses to treat disease.

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Competing against science fiction

David Kramer's piece (PHYSICS TODAY, July 2012, page 23) concerning the importance of science to the general public and the public's discomfort with science has provoked me to respond.

Science is dull and dreary to the general public and will remain so until we can achieve warp speed. James Kirk and Han Solo achieve it regularly and without ill effect. The public knows from Star Trek and Star Wars that warp speed is possible, if only we put the effort into it. Likewise, gravity is just an inconvenience to be overcome, and the public knows it can be overcome with little effort, to take us to the stars.

Let's face it, when the public is excited about such events as the space program, Moon landings, and such, it is a triumph of technology, not science. All the science education in the world will not overcome the siren call of science fiction; it's simply too exciting.

All one can hope for is that the small minority of the general public who appreciate science and scientific endeavors are those who have influence in the public media and the halls of Congress. In that regard we have been pretty damn lucky.

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