periments should allow numerous tests of the relation between neural properties and learning, from the behavioral to the molecular levels.

References and Notes

1. S. J. Chew, D. S. Vicario, F. Nottebohm, *Science* **274**, 1909 (1996).
2. C. V. Mello, D. S. Vicario, D. F. Clayton, *Proc. Natl. Acad. Sci. U.S.A.* **89**, 6818 (1992).
3. C. V. Mello, F. Nottebohm, D. F. Clayton, *J. Neurosci.* **15**, 6919 (1995).
4. S. J. Chew, C. Mello, F. Nottebohm, E. Jarvis, D. S. Vicario, *Proc. Natl. Acad. Sci. U.S.A.* **92**, 3406 (1995); S. J. Chew, D. S. Vicario, F. Nottebohm, *ibid.* **93**, 1950 (1996); R. Stripling, S. F. Volman, D. F. Clayton, *Soc. Neurosci. Abstr.* **20**, 165 (1994); *ibid.* **21**, 959 (1995).
5. R. W. Thompson and A. Spencer, *Psychol. Rev.* **173**, 16 (1964); V. F. Castellucci, T. J. Carew, E. R. Kandel, *Science* **202**, 1306 (1978).
6. L. Li., E. K. Miller, R. Desimone, *J. Neurophysiol.* **69**, 1918 (1993); J. L. Ringo, *Behav. Brain Res.* **76**, 191 (1996).
7. T. J. Carew, H. M. Pinsker, E. R. Kandel, *Science* **175**, 451 (1972); J. Byrne, *J. Neurophysiol.* **48**, 431 (1982); C. H. Ramkin and B. S. Broster, *Behav. Neurosci.* **106**, 239 (1992); T. Tully, T. Preat, S. C. Boynton, M. Del Vecchio, *Cell* **79**, 35 (1994).
8. W. Wickelgren, *J. Math. Psychol.* **9**, 418 (1972).
9. H. P. Davis and L. R. Squire, *Psychol. Bull.* **96**, 518 (1984); P. G. Montarolo *et al.*, *Science* **234**, 1249 (1986); P. V. Nyugen, T. Abel, E. R. Kandel, *Science* **265**,1104, (1994).
10. G. Greksch and H. Matthies, *Pharmacol. Biochem. Behav.* **12**, 663 (1980); F. Freeman, S. P. R. Rose, A. B. Scholey, *Neurobiol. Learn. Mem.* **63**, 291 (1995).
11. J. DeZazzo and T. Tully, *Trends Neurosci.* **18**, 212 (1995).
12. E. K. Miller and R. Desimone, *Science* **263**, 520 (1994).
13. J. Sobotka and J. L. Ringo, *J. Neurosci.* **16**, 4222 (1996).

14. I thank M. Brainard, D. Buonomano, T. Carew, J. Maunsell, and L. Squire for their suggestions and for critical reading of earlier versions of this commentary.

CONDENSED MATTER PHYSICS

The Metal-Insulator Transition in Correlated Disordered Systems

Elihu Abrahams and Gabriel Kotliar

Most substances in nature are either good metals (conductors) or good insulators. Continuous metal-to-insulator transitions are notably difficult to realize experimentally at very low temperatures. Coaxing materials to the proximity of the metal-to-insulator transition region requires clever experimental design, the choice of a suitable material, and the application of an external parameter to drive the system through the transition. Furthermore, in most systems, even a continuous change in external parameters results in a discontinuous first-order metal-to-insulator transition. Until now, continuous metal-to-insulator transitions have been realized only in amorphous alloys and in doped semiconductors. However, Husmann and colleagues have succeeded in observing a continuous metal-to-insulator transition at very low temperature by applying pressure to the chalcogenide compound $Ni(S,Se)_2$. Their results appear on page 1874 of this issue (*1*).

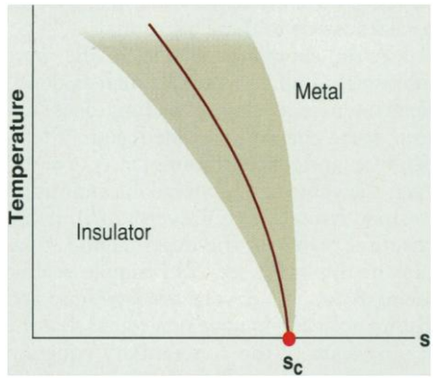
How a metal can be turned into an insulator by continuously varying external parameters has fascinated physicists for the last four decades. A metal-insulator transition is characterized by the localization of the charge carriers, which prevents them from transporting an electric current. The two basic mechanisms that cause electron localization are the correlations among the electrons and the disorder present in the sample. Mott demonstrated that electron-electron interactions can produce a metal-insulator transition even in a system without disorder (*2*). Anderson discovered that disorder, such as strong spatial fluctuations in the electrostatic potential caused by impurities, can drive a metal-insulator transition in a system of noninteracting electrons (*3*). The theoretical description of the situation when both effects are present is a central unsolved problem, especially when the electron-electron interactions are strong.

An important advance in our understanding came with the introduction of scaling ideas (*4*). The scaling approach had proved to be extraordinarily successful for understanding phase transformations driven by temperature. Near a continuous second-order phase transition, a simple and universal description of the transition emerges because the physics is controlled by a diverging length scale that is much larger than any of the microscopic lengths in the problem.

There is a sharp qualitative distinction between metal and insulator only at zero temperature because insulators can carry a (small) current at nonzero temperature owing to thermal excitations. Thus, a continuous metal-insulator transition can only take place at zero temperature. The metal insulator transition is therefore an example of a quantum phase transition—that is, a transition caused by a fundamental change in the ground state of a system as a parameter is varied.

A phase diagram can be constructed for such a transition (figure). A variety of parameters can be used to tune a system through the transition. In the figure, the abscissa is the control parameter. At nonzero temperature, two scenarios are possible. One is that there is a line of first-order metal-insulator transitions terminating in the critical point at $T = 0$ (solid line). The other is that there is simply a continuous crossover (shaded region) from metallic (resistivity decreases as T decreases) to insulating (resistivity increases) behavior.

The simplest scaling scenario gives the result that at low temperatures, and very near the metal-insulator transition, the electrical conductivity has a rather simple form: $\sigma(T, s) = \xi(s)^{-\mu\nu} f[T\tau(s)]$, where T is the absolute temperature. This formula is remarkable because it states that all of the dependence on material parameters of a system near the metal-insulator transition is contained in the value of a length scale ("localization length") $\xi(s)$ that diverges as $(s - s_c)^{-\nu}$ and a time scale $\tau(s)$ that diverges as temperature approaches zero as $(s - s_c)^{-\nu z}$; s is the critical parameter (for example, pressure or impurity concentration), which drives the metal-insulator transition when $s \rightarrow s_c$. The numbers μ, z, and ν introduced here are critical exponents. μ describes how the conductivity vanishes at zero temperature as s is varied through s_c, that is, $\sigma \propto (s - s_c)^{\mu}$. The slowing down in the relaxation that accompanies a phase transition is quantified by means of a "dynamical



Phase diagram for a metal-insulator transition at the quantum critical point. At $T = 0$, the behavior is metallic for critical parameter $s > s_c$ and insulating for $s < s_c$. The solid line indicates a line of first-order transitions; the shading shows the crossover region.

The authors are at the Serin Physics Laboratory, Rutgers University, Piscataway, NJ 08855, USA. E-mail: kotliar@physics.rutgers.edu

critical exponent" z. In ordinary phase transitions, because the behavior is governed by a diverging length scale, the critical exponents are universal and largely independent of the specific microscopic details of the system. They depend only on a few fundamental general properties such as the space dimensionality and the symmetry of the low-temperature phase. The critical vapor-to-liquid transition, for example, has the same critical exponents as the transition between the paramagnetic and ferromagnetic phases of an anisotropic magnet; they belong to the same universality class.

Some of the fundamental questions include: Is there any scaling at all near the metal-insulator transition? If so, is simple scaling, as in the conductivity equation, obeyed? How many different universality classes of metal-insulator transitions are there? What determines a universality class? In other words, what are the "relevant parameters" in this problem that play the role of "symmetry of the order parameter" in ordinary critical phenomena? If scaling is indeed obeyed, a more refined question is whether a relation known as hyperscaling, $\mu = (d-2)\nu$ (where d is the space dimensionality), connecting the conductivity exponent μ with the exponent that characterizes the divergence of the localization length ν, holds. Finally, one would like to have microscopic calculations of the exponents and scaling functions within a model in each universality class. Surprisingly, in spite of more than two decades of intensive work, we have only partial answers to these questions.

On the experimental side, in the more intensively studied materials such as doped semiconductors, simple scaling does not seem to be obeyed in a wide region of temperatures and concentrations (*5*). As a result, even the value of the critical concentration in these systems is controversial (*6*). [For a beautiful review of the experimental situation in this field, see (*7*).] Simple scaling seems to apply to very few systems, and Husmann *et al.* (*1*) have now found that the scaling form of the conductivity equation does fit their data fairly well with an expected $\mu \cong 1$ but with an unexpected $z\nu \cong 4.6$. There is no explanation for the latter result.

This experiment is significant because $Ni(S,Se)_2$ is a material in which the electron-electron interaction is very strong and because this system does not undergo a structural change across the metal-insulator boundary. Structural changes are rather common and usually cause the metal-insulator transition to be discontinuous. For example, the metal-insulator transition in another archetypical strongly correlated system V_2O_3 is a discontinuous first-order one (*8*).

A variety of parameters have been used to tune several material systems through the metal insulator transition. The table shows an incomplete summary of critical exponents measured in systems where in some region of parameters the metal-insulator transition appears to be continuous. The exponents are not known to good accuracy. For each experiment, the corresponding control parameter is denoted in the last column of the table.

On the theoretical side, there have been several suggestions that more complicated scaling laws are necessary to describe the transition. Generalizations of the conductivity equation to incorporate different time scales associated with spin and charge fluctuations have been proposed (*9*). A scenario containing an infinite number of time scales, a situation reminiscent of a glass, has recently been suggested (*10*).

Material	Critical exponents		Tuning parameter
	μ	$z\nu$	
Si-Au (*12*)	1	2	Concentration
$Al_{0.3}Ga_{0.7}As$ (*13*)	1	2	Photointensity
InO (*14*)	1	4	Annealing time
$Ni(S,Se)_2$ (*1*)	1	4.6	Pressure
GaAs (*15*)	1	3	Magnetic field

Critical exponents at the metal-insulator transition. In InO, the metal-insulator transition is preempted by a superconducting transition.

The new experiment tells us that there is at least one strongly correlated system which can undergo a zero temperature quantum phase transition between a metallic and an insulating state. In addition, that transition exhibits scaling with novel critical exponents. However, this experiment raises again many old questions.

Why are the critical indices in this system so different from what is observed in doped semiconductors and amorphous alloys? Is the present universality class associated with the unusual strength of the electron-electron correlations that are present in this material? Or is it a consequence of the magnetic order that exists in both the metallic and the insulating phases?

Much more work needs to be done to unravel the metal-insulator transition puzzle. The application of experimental probes such as neutron scattering to $Ni(S,Se)_2$ will reveal how the spin degrees of freedom evolve as the charge carriers are localized. Thermodynamic measurements should tell us if quantities such as the specific heat exhibit scaling near the metal-insulator transition. A direct probe of the wave-vector dependence of the charge fluctuations could extract directly the behavior of the localization length and verify the hyperscaling hypothesis. Finally, high-resolution angle-resolved photoemission experiments (*11*) have begun to probe the electron spectral function near the first-order metal-insulator transition, which takes place in $Ni(S,Se)_2$ at high temperatures. An extension of these measurements to very low temperatures, where quantum effects are dominant and the transition is continuous, would provide a direct measurement of the one-particle density of states, another physical quantity that is expected to vanish as one approaches a continuous metal-insulator transition.

During the last decade there has been a revival in the synthesis and characterization of transition metal oxides and related compounds. This rebirth opens new avenues to revisit the metal-insulator transition. In addition to the traditional materials, such as $Ni(S,Se)_2$ and V_2O_3, new quaternary compounds can now be designed and synthesized. Such new developments in materials science are likely to result in improved studies of the metal-to-insulator transition. Furthermore, as we learn to control this delicate state of matter, practical applications of the effect will follow.

Stimulated in part by the development of a variety of materials whose physical properties are determined by the presence of strong electron-electron interaction, theorists have been developing new mathematical tools for treating its consequences. They are currently being applied to study the Mott-Anderson transition. We expect rapid progress in this field in the years to come.

References and Notes

1. A. Husmann *et al.*, *Science* **274**, 1874 (1996).
2. N. F. Mott, *Metal-Insulator Transitions* (Taylor and Francis, London, 1974).
3. P. W. Anderson, *Phys. Rev.* **109**, 1498 (1958).
4. F. Wegner, *Z. Phys. B* **25**, 327 (1976); E. Abrahams, P. W. Anderson, D. C. Licciardello, T. V. Ramakrishnan, *Phys. Rev. Lett.* **42**, 673 (1979).
5. For a comprehensive review, see D. Belitz and T. Kirkpatrick, *Rev. Mod. Phys.* **66**, 261 (1994).
6. T. Rosenbaum *et al.*, *Phys. Rev. B* **27**, 7509 (1983); H. Stupp *et al.*, *Phys. Rev. Lett.* **71**, 2634 (1993); T. Rosenbaum *et al.*, *ibid.* **72**, 2121 (1994); H. Stupp *et al.*, *ibid.*, p. 2122.
7. M. P. Sarachik, in *The Metal to Non-Metal Transition Revisited*, P. P. Edwards and C. N. R. Rao, Eds. (Taylor and Francis, London, 1996), p. 79.
8. S. Carter *et al.*, *Phys. Rev. Lett.* **67**, 3440 (1991).
9. A. M. Finkel'shtein, *Sov. Phys. JETP Lett.* **37**, 517 (1983); C. Castellani, G. Kotliar, P. A. Lee, *Phys. Rev. Lett.* **56**, 1179 (1987).
10. D. Belitz and T. R. Kirkpatrick, *Phys. Rev. B* **52**, 13922 (1995).
11. A. Y. Matsuura *et al.*, *ibid.* **53**, 7584 (1996).
12. D. J. Bishop, E. G. Spencer, R. C. Dynes, *Solid State Electron.* **28**, 73 (1985).
13. S. Katsumoto *et al.*, *J. Phys. Soc. Jpn.* **56**, 2259 (1987).
14. A. Hebard and M. Palaanen, *Phys. Rev. Lett.* **52**, 2057 (1984).
15. M. C. Maliepard *et al.*, *ibid.* **61**, 369 (1988).