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information. In the mean time, they have modified their setup and can now communicate random bits of information at data rates in excess of 150 Mbits s^{-1} (8) (see figure). The theory for this experiment was developed by Abarbanel and Kennel (9), building on the ideas suggested earlier by Rulkov and Volkovskii (7).

These preliminary but intriguing results suggest that chaos-based applications may be more than just a laboratory curiosity, although substantial research must be undertaken to transfer such discoveries to the commercial sector. For example, the level of security afforded by this scheme and the effects of communication channel distortion and fading must be fully addressed. In addition, nonlinear-dynamics researchers have yet to develop a general, systematic method for designing new nonlinear systems suitable as chaos transmitters and receivers. In light of the interest expressed by corporations and governments in such laboratory demonstrations, I expect that many of these issues will be tackled in the near future.

References and Notes

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CONDENSED MATTER PHYSICS

Superconductivity Compatibility

Anthony J. Leggett

Twelve years after the original discovery of superconductivity above 30 K in a cuprate material, and despite its subsequent achievement at temperatures ranging up to 160 K in a vast number of different materials of this class, the mechanism of superconductivity remains as contentious as ever. The cuprates are characterized by the existence of relatively well-separated planes consisting of copper and oxygen atoms (CuO_2 planes), and the general belief is that the electrons which carry the superconducting current reside at least primarily in these planes.

Most current theories of the mechanism are intraplane models, that is, they assume that the essentials can be understood by focusing on the mutual interactions of the electrons within a single CuO_2 plane and that any interplane contact, either by tunneling or through the Coulomb interaction, is secondary. An important exception is the interlayer tunneling (ILT) model of Anderson and his collaborators (*1*), whose essentials I outline below; this theory is further distinguished from many of its competitors by the fact that it makes at least one quantitative and parameter-free prediction. Two research reports in this issue make important if prima facie contradictory inputs into the debate on the compatibility of this prediction with the experimental data: On page 1196, Anderson (*2*) discusses the relation of the ILT model to some key superconducting materials, and on page 1193, Moler *et al.* (3) present data on one of the compounds.

In the ILT model, the tunneling of single electrons between neighboring CuO_2 planes (along the *c* axis) in the normal state is postulated to be blocked. (In Anderson's original version of the model, the blockage was caused by the unusual nature of the electron states within each plane, but this feature is not essential to the present discussion.) As in the traditional theory of superconductivity, the onset of this phenomenon corresponds to the formation of Cooper pairs (bound pairs of electrons resembling extended "di-electronic molecules"). However, in the ILT model, the energy saving that drives the formation of the pairs does not come, as in the traditional theory, from an effective electron-electron attraction mediated by exchange of virtual lattice vibrations, but rather from the fact that the pairs, as distinct from the single electrons, can tunnel much more readily between neighboring CuO_2 planes; as a consequence of the uncertainty principle (if perhaps counter to one's initial intuition), the effect of this easy motion along the *c* axis is to decrease the associated kinetic energy and therefore make the formation of Cooper pairs energetically favorable.

Around and around. Image of an interlayer Josephson vortex in $Tl_2Ba_2CuO_{6+\delta}$ [from Moler *et al.* (*2*)]. The width of the vortex is determined by experimental resolution and so is not of fundamental significance; the height, on the other hand, is a measure of the London penetration depth λ_c.

Now, Cooper pairs tunneling along the *c* axis can carry a supercurrent in this direction, and one might therefore expect that in the ILT model there should be some relation between the "strength" of the supercurrent and the energy that is saved by the tunneling and thus available for pair formation (in other words, for condensation into the superconducting state). This is true; in fact, for single-plane cuprates—that is, those in which all pairs of neighboring CuO_2 planes are equivalent—the model in its current version predicts that the energy of condensation E_{cond} should be directly proportional to the inverse square of the so-called London penetration depth for currents flowing along the *c* axis (usually denoted λ_c): $E_{cond} = A\lambda_c^{-2}$, where the constant A depends only on known geometrical factors. A check of this prediction for the various single-layer cuprates should thus constitute a critical test of the ILT model.

In the ideal experiment, a single sample of each known single-plane cuprate would be measured directly for both E_{cond} and λ_c. In real life, for practical reasons, the experiments are usually done on different samples, and of the half-dozen-odd single-plane cuprates currently known, many display a degree of intersample variability, such as to make the result of such a procedure meaningless; in addition, existing measurements of λ_c are often indirect and mutually inconsistent. However, at least three single-plane materials are usually believed to be sufficiently well-characterized and reproducible that intersample comparisons may be legitimate, and moreover may allow relatively direct measurements of λ_c, namely $HgBa_2CuO_{4+\delta}$ (Hg-1201), $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201), and $La_{2-x}Sr_xCuO_4$ (LSCO), where the oxygen doping δ or strontium dop-

The author is in the Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. E-mail: tony@cromwell.physics.uiuc.edu

ing x can vary over a wide range. In his report in this issue (*2*), Anderson collates the available data for E_{cond} and λ_c for these materials. In the case of LSCO, he obtains E_{cond} for three different values of x by integrating the directly measured specific heat, and obtains λ_c for roughly corresponding values of x by a plausible ansatz for the optical data (he notes that the values so obtained are consistent with those measured directly); acknowledging that the errors are considerable, he points out that the correlation between E_{cond} and λ_c as x is varied is precisely of the nature predicted by the ILT model, and argues that this cannot be a coincidence. In the case of Hg-1201, suitable thermodynamic data are not available, but by a plausible scaling argument, Anderson obtains a value of E_{cond} and hence a prediction, in the ILT model, of λ_c of 1.0 ± 0.5 μm. He then cites a recent paper (*4*) that, on the basis of magnetic susceptibility measurements on oriented powders of this material, infers a value of λ_c of 1.36 ± 0.16 μm; Anderson characterizes the agreement with the ILT prediction as "spectacular."

Enter, however, Tl-2201. For samples of this material near optimum doping, the condensation energy has been directly measured, and there is general agreement that the value of λ_c predicted by the ILT model is in the region of 1 μm, with error bars of at most a factor of 2; this prediction is spectacular, because on the basis of an empirical rule of thumb correlating λ_c with the (measured) normal-state c-axis resistivity, one would expect a much larger value (a discrepancy that is absent, or much less severe, in LSCO and Hg-1201). In earlier work, van der Marel and his collaborators (*5*) inferred from the absence of a c-axis plasma resonance peak in their optical data that λ_c must be at least 15 μm, but they did not establish the actual value of this quantity. In a report in this issue (*3*), Anderson's colleague Moler and her collaborators use an elegant magnetic imaging technique (see figure) to measure λ_c directly, with the result $\lambda_c = 19 \pm 2$ μm, about 20 times the ILT prediction. This discrepancy is acknowledged by Anderson to constitute a major difficulty for the ILT model; however, he argues that Tl-2201 is the only known case where its predictions are apparently inconsistent with the data and speculates that the material may manifest subtle metallurgical complications and not be a true single-plane material.

Thus, the current state of play with respect to the ILT model is that Tl-2201, assuming it really is a true single-plane material, contradicts its predictions by a large margin, whereas LSCO and [if the λ_c value from Panagopoulos *et al.* (*4*) is accepted] Hg-1201 can be argued not merely to confirm the model but to do so in a way that is too striking to be accidental. A final resolution may require reexamination of the structure of Tl-2201, more direct (by imaging, for instance) measurements of λ_c for Hg-1201, and combined thermodynamic and electromagnetic measurements on single samples of these and other one-plane materials.

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EVOLUTION

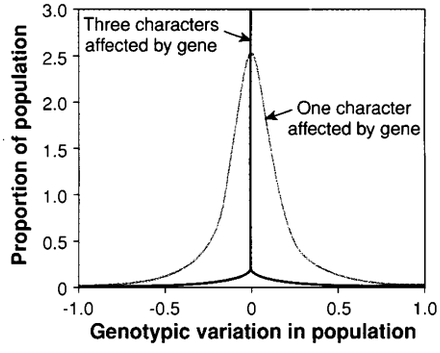
Complexity Matters

Günter Wagner

Are organisms like liquid droplets, infinitely malleable by the changing forces of evolution, or do they contain a "frozen core"—the Bauplan, or body design, which remains little changed under the varying adaptive pressures a lineage encounters during its history? Until quite recently, these questions have divided evolutionary biologists (as well as philosophers) into two almost nonoverlapping camps. On the one hand are the so-called reductionists, largely recruited from the ranks of population genetics and associated disciplines, who are strongly committed to the adaptationist program of evolutionary biology. This group tends toward a world view in which there are no limits to an organism's variability and its ability to evolve. On the other hand are those biologists who primarily study whole organisms or complex phenotypic traits of organisms. This second group emphasizes the need to understand the constraints on evolutionary change that arise as a consequence of the intrinsic functional and developmental complexity of organisms. On page 1210 of this issue, Waxman and Peck (*1*) present a new mathematical result that reconciles most of the differences between these two camps. Population genetic equations predict, so they show, that parts of the phenotype effectively "crystallize" as the complexity of systems increase. But what is the problem to which this result is the solution?

The intellectual history of the problem goes back to the synthesis of Darwinian evolutionary theory and Mendelian genetics forged by the fathers of modern evolutionary theory, R. A. Fisher, S. Wright, and T. Dobzhansky. Through the marriage of genetics and Darwinism, it became clear that the process of evolution can be understood, or at least described, as changes in gene frequencies over time (*2*). New genes arise by mutation and are either lost (most likely) or they replace their parental genes, by selection or genetic drift. This, it turns out, is the most elementary level on which evolution can be explained. Consequently, a lot of effort was and continues to be invested in research directed at understanding these elementary processes. This remarkably successful research program has been pursued with the implicit assertion that evolution of real and complex organisms is just more of the same, and that no qualitatively new phenomena emerge as a result of increasing complexity (*3*). In this view, complexity is fundamentally irrelevant to an understanding of evolution. A corollary of this line of thinking is that all aspects and characters of the organism are variable and constantly changing (although at different rates), and the concept of a "Bauplan" (the body organization characteristic of a larger group of organisms) is an illusion (*4*).

A well-informed minority of organismal biologists, however, never were convinced of this radical view. Theirs is a more pluralistic view: yes, they agree, many characters are highly variable and their differences



Evolutionary crystallization. As the number of characteristics affected by a gene increases from one (blue) to three (red), one genotype becomes dominant.

The author is in the Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT 06520-8106, USA. E-mail: gpwag@peaplant.biology.yale.edu