Questions inevitably remain. Is the dynamic behavior of MeCP2 associated with the *BDNF* or *Hairy2a* gene promoters the exception or the rule? What other genes are induced when MeCP2 becomes phosphorylated? Which are the genes whose misregulation causes Rett syndrome? The explosion of knowledge about DNA methylation and the brain is at last making these questions experimentally accessible.

References

1. R. E. Amir *et al.*, *Nat. Genet.* **23**, 185 (1999).
2. M. Tudor *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **99**, 15536 (2002).
3. W. G. Chen *et al.*, *Science* **302**, 885 (2003).
4. K. Martinowich *et al.*, *Science* **302**, 889 (2003).
5. I. Stancheva *et al.*, *Mol. Cell* **12**, 425 (2003).
6. A. E. West *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **98**, 11024 (2001).
7. X. Nan *et al.*, *Nature* **393**, 386 (1998).
8. T. Jenuwein, C. D. Allis, *Science* **293**, 1074 (2001).
9. E. Li *et al.*, *Cell* **69**, 915 (1992).
10. A. Eden *et al.*, *Science* **300**, 455 (2003).
11. S. Kriaucionis, A. Bird, *Hum. Mol. Genet.* **12**, R221 (2003).
12. A. S. Hutchins *et al.*, *Mol. Cell* **10**, 81 (2002).

PHYSICS

Searching for Gravity's Hidden Strength

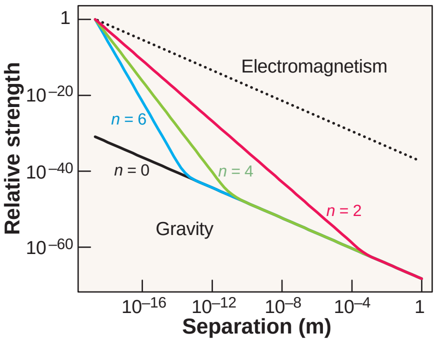
Jonathan L. Feng

Of the four known fundamental forces—gravity, electromagnetism, and the weak and strong forces—gravity is by far the weakest. The reasons for this weakness have long remained enigmatic. Recent proposals suggest, however, that the weakness of gravity may be evidence for extra spatial dimensions. Experiments ranging from tabletop tests of Newtonian gravity to searches for microscopic black holes in kilometer-scale detectors are now putting these ideas to the test.

The importance of gravity in everyday life results not from its strength but from its universality: Objects cannot be gravitationally neutral, and all bodies with mass attract. Yet as an interaction between elementary particles, gravity is extremely weak. For example, the gravitational attraction between two protons is 35 orders of magnitude weaker than their electromagnetic repulsion. This holds for protons separated by any distance r, because both gravitational and electromagnetic forces are proportional to $1/r^2$.

The observed weakness of gravity may, however, not be an intrinsic property of gravity, but may instead be an effect of extra spatial dimensions. This possibility is based on a simple consideration. Suppose that our three-dimensional (3D) world is merely a subspace of a higher-dimensional space, and that gravity propagates freely in all dimensions, but that all other forces are confined to our three dimensions. In contrast to the familiar three dimensions, the extra dimensions are curled up in small circles of circumference L. Hence, moving a distance L in the direction of any of the extra dimensions brings one back to one's starting place.

Now suppose that at some separation distance $r < L$, gravity is strong, that is, comparable to electromagnetism. As r increases, the electromagnetic force drops as $1/r^2$. However, the gravitational field spreads out in all available spatial dimensions, and the gravitational force therefore decreases much more rapidly as $1/r^{2+n}$, where n is the number of extra dimensions. This rapid drop continues until $r > L$, at which point the extra dimensions become less and less important and gravity recovers its $1/r^2$ behavior (see the figure).



Gravity in extra dimensions. The strength of gravity for various numbers of large extra dimensions n is compared to the strength of electromagnetism (dotted). Without extra dimensions, gravity is weak relative to the electromagnetic force for all separation distances. With extra dimensions, the gravitational force rises steeply for small separations and may become comparable to electromagnetism at short distances.

If this picture is correct, then gravity is not intrinsically weak: It is as strong as electromagnetism at small length scales. It appears weak at the relatively large distances of common experience only because its effects are diluted by propagation in extra dimensions. The distance at which the gravitational and electromagnetic forces might have equal strength is unknown, but a particularly interesting possibility is that it is 10^{-19} m, the distance at which the electromagnetic and weak forces are known to unify to form the electroweak force (*1*).

A priori, the size of the extra dimensions L and their number n are independent parameters. However, to achieve equality of gravitation and electromagnetic forces at 10^{-19} m, they become constrained by the relation

$$L \approx 10^{(32/n)-19}\ \mathrm{m} \qquad (1)$$

For large n, the strength of gravity grows very rapidly at microscopic length scales. Gravity may then deviate from its $1/r^2$ behavior only at very small distances and still be comparable to electromagnetism at 10^{-19} m.

This scenario, called "large extra dimensions" because the length L of Eq. 1 is large relative to typical length scales in particle physics, raises many more questions than it answers. When first proposed, perhaps its most surprising aspect was that such a bold modification of Newtonian gravity was not immediately excluded by data. Now, however, a wide variety of experiments are reaching the sensitivity required to test these speculative ideas. In combination, they probe all possible values for the number of extra dimensions, placing the entire scenario on the threshold of detailed investigation.

The possibility of one large extra dimension is untenable. It requires the extra dimension to be of size $L \approx 10^{13}$ m, a length scale where the $1/r^2$ gravitational force law is clearly still valid. For two extra dimensions, each extra dimension would have $L \approx 1$ mm. Sensitive tests of gravity are notoriously difficult at such length scales. Nonetheless, recent tabletop experiments with torsion pendulums have excluded significant deviations from the $1/r^2$ force law at length scales as small as 0.1 mm (*2*).

Astrophysical observations provide less direct but more stringent constraints on low numbers of extra dimensions (*3*, *4*). For two extra dimensions, for example, the gravitational force would be enhanced at large enough length scales that supernovae should release much of their energy as gravitational energy—in conflict with observations. These constraints, which were noted immediately after the proposal of large extra dimensions, exclude scenarios with few extra dimensions.

The challenge, then, has been to explore large numbers of extra dimensions, such as the six or seven favored by string theory. In such cases, tabletop and astrophysical constraints are ineffective, because the predicted deviations from Newtonian gravity oc-

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cur on length scales far below those that are currently accessible. The most promising approach is to look not for small effects at relatively large length scales, but for large effects at the smallest possible length scales, where gravity is predicted to be strong. These probes are equally powerful for any *n*. For low *n*, they are superseded by those discussed above, but for large *n*, they provide the leading experimental tests.

Perhaps the most remarkable possibility for testing large *n* has been the realization that if gravity is strong at 10^{-19} m, tiny black holes may form in high-energy particle collisions (*5*–*8*). The formation of a black hole is expected when a large mass or, equivalently, a large energy is concentrated in a small volume (*9*, *10*). In the conventional 3D world, gravity is so weak that the required energy density is never achieved in observable particle collisions. However, if large extra dimensions exist and gravity is intrinsically strong, very high energy particles occasionally pass close enough to each other to trigger gravitational collapse, forming microscopic black holes. Like conventional black holes, these black holes are expected to emit "Hawking radiation," which leads to the evaporation of the black holes. In contrast to the astrophysical variety, however, they are tiny, with diameters on the order of 10^{-19} m, and evaporate explosively after only 10^{-27} s.

Today's particle colliders are not sufficiently energetic to produce microscopic black holes. However, ultrahigh-energy cosmic rays have been observed to collide with particles in Earth's atmosphere with center-of-mass energies that are 100 times those available at human-made colliders. The ultrahigh-energy neutrinos that are expected to accompany these cosmic rays may create microscopic black holes. Although these black holes are extremely short-lived and hence impossible to detect directly, their explosive evaporations produce events with unusual properties (*7, 8*). The fact that no such events have been observed so far places strong constraints on large extra dimensions, but does not yet exclude these scenarios altogether (*11*).

The search for large extra dimensions will intensify. The currently operating Antarctic Muon and Neutrino Detector Array and its successor IceCube are kilometer-scale cosmic neutrino detectors buried deep in the Antarctic ice. The Auger Observatory, consisting of water Cerenkov detectors covering a 3000-km^2 area in the high desert of Argentina, will also begin operation in 2 to 3 years. These large projects will provide enhanced sensitivity to the putative microscopic black holes (*12, 13*). The Large Hadron Collider, currently under construction in Geneva, will provide an even higher sensitivity to large extra dimensions.

If no anomalous effects are seen in these ambitious projects, the possibility of large extra dimensions will be excluded. If seen and confirmed, however, these effects will provide the first evidence for strong gravity and a radically new view of spacetime.

References

1. N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali, *Phys. Lett. B* **429**, 263 (1998).
2. E. G. Adelberger *et al.*, http://arXiv.org/abs/hep-ex/0202008 (2002).
3. S. Cullen, M. Perelstein, *Phys. Rev. Lett.* **83**, 268 (1999).
4. L. J. Hall, D. R. Smith, *Phys. Rev. D* **60**, 085008 (1999).
5. S. B. Giddings, S. Thomas, *Phys. Rev. D* **65**, 056010 (2002).
6. S. Dimopoulos, G. Landsberg, *Phys. Rev. Lett.* **87**, 161602 (2001).
7. J. L. Feng, A. D. Shapere, *Phys. Rev. Lett.* **88**, 021303 (2001).
8. L. A. Anchordoqui, H. Goldberg, *Phys. Rev. D* **65**, 047502 (2002).
9. D. M. Eardley, S. B. Giddings, *Phys. Rev. D* **66**, 044011 (2002).
10. H. Yoshino, Y. Nambu, *Phys. Rev. D* **66**, 065004 (2002).
11. L. A. Anchordoqui *et al.*, http://arXiv.org/abs/hep-ph/0307228 (2003).
12. M. Kowalski, A. Ringwald, H. Tu, *Phys. Lett. B* **529**, 1 (2002).
13. J. Alvarez-Muniz *et al.*, *Phys. Rev. D* **65**, 124015 (2002).

ECOLOGY

Vole Stranglers and Lemming Cycles

Peter J. Hudson and Ottar N. Bjørnstad

For more than 80 years, population ecologists have been preoccupied with the rise and fall in population numbers among small mammal species, but they still cannot agree on the reasons for these cyclic variations in abundance. The controversy arises from three central questions: What are the ecological mechanisms that generate fluctuations in these cycles? Are these mechanisms common to all cyclic populations? Does understanding of these mechanisms allow us to explain why some populations are cyclic whereas others are not? The debate has been so heated among small mammal researchers that other ecologists jokingly refer to them as the "vole stranglers." On page 866 of this issue, Gilg *et al.* (*1*) present their long-term field study of the cyclic dynamics of collared lemmings (*Dicrostonyx groelandicus*) in northeastern Greenland and describe how these dynamics are affected by predators. The mathematical model that the investigators develop illustrates how the cyclic fluctuations of collared lemmings are driven by predation by the lemming specialist, the stoat, and then are molded (when lemming populations reach high densities) by three generalist predators: the arctic fox, the snowy owl, and the long-tailed skua (see the figure). The new work answers the first question and provides key insights into the third question.

The saying "Lemmings cycle—unless they don't" (*2*) embodies the enigma of cyclic fluctuations in many lemming and vole populations inhabiting boreal and arctic ecosystems. The collared lemming is an excellent example: Some populations exhibit violent and periodic fluctuations in their numbers, whereas others exhibit no clear statistical pattern (*3*). The "vole stranglers" have come up with many hypotheses to account for this paradox. A favorite is the so-called specialist predator hypothesis, which postulates that small mammal populations undergo periodic fluctuations in numbers in response to predation by a specialized predator (*4*). This hypothesis has taken center stage because the fundamental theory of predator-prey interactions—encapsulated in the worthy Lotka-Volterra model—predicts cycles in prey and predator abundance. Hence, it is natural to consider that a predator (or some other specialist consumer) is the crucial player in the cyclic dynamics of small mammal populations. At a more detailed level, theory predicts that interactions between a specialized predator and its main prey—such as the stoat's predation of collared lemmings—should result in cycles in which the peak in predator numbers lags behind that of its prey by one-quarter of a cycle (*4*). This prediction is beautifully borne out by the Gilg *et al.* study (*1*). Indeed, this is one of those rare instances when nature appears to reflect basic theory—a textbook case.

One important feature of the specialist predator hypothesis is that a second stabilizing effect is needed at high lemming densities to slow down the growth rate of the prey and allow the specialist predator to catch up and drive prey abundance downward (*5*). The collared lemming is, again, a wonderful illustration. The cyclic fluctuations in lemming populations in northeastern Greenland appear to result from the tension between the

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