

The weight of expectation

C. D. Hoyle

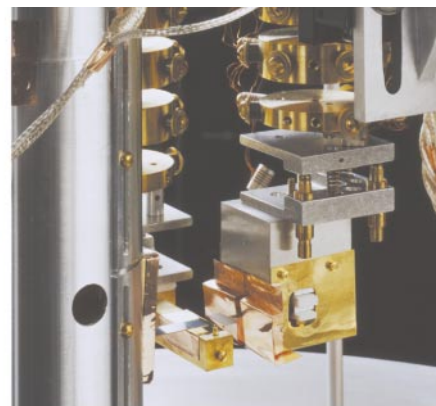
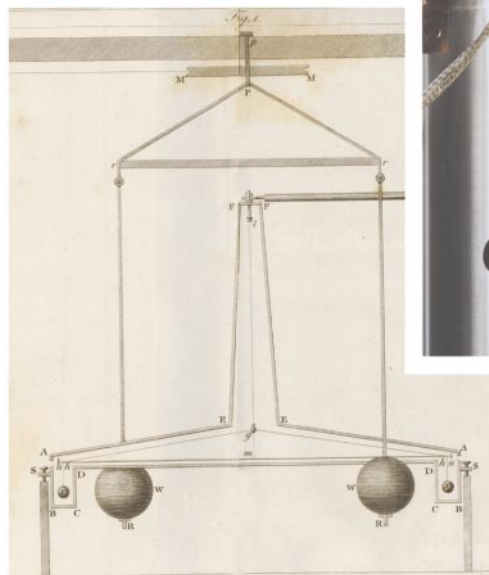
Newton devised his universal law of gravitation for planets, but does it work at small scales? A search for a deviation from the expected behaviour could provide the first evidence in support of string theory.

Gravity, one may think, is a rather well understood subject. It has been more than 300 years since Isaac Newton determined that the magnitude of the gravitational force, F , between two bodies of masses M and m (separated by astronomical distances) depends on the inverse-square of the distance, r , between them: $F = GMm/r^2$. And we have recently passed the two-century mark since Henry Cavendish made his first measurement¹ of the gravitational constant, G , which sets the fundamental strength of the interaction.

But developments in theoretical physics predicting possible deviations from the inverse-square law at small distances² have brought about a renewed enthusiasm for precise laboratory tests of this most familiar fundamental force. The results reported by Joshua Long and colleagues³ on page 922 of this issue describe an investigation of gravity at a previously unexplored scale. Furthermore, Long *et al.* have devised a new apparatus, in place of the low-frequency torsion balance that has been the workhorse of laboratory-scale gravitational experiments since the time of Cavendish^{4–6} — they use a kilohertz, resonant-oscillator technique to test the gravitational force experienced by test masses that are separated by just 108 μm (Fig. 1).

Gravity may have been the first of the fundamental forces to be described mathematically, but it is still the most poorly characterized. The inverse-square-distance dependence established by Newton had been assumed to hold true at short distances, but only recently has gravity actually been shown to exist between objects separated by less than one millimetre⁵.

Why is it so difficult to measure the properties of gravity, when it obviously exerts a strong influence on us every day? The reason is that gravity is incredibly weak compared with the other known fundamental forces of nature (electromagnetism, and the strong and weak forces). We feel gravity only because, unlike electromagnetism, it cannot be shielded with 'negative' masses — there is no gravitational repulsion to balance the attraction. To put the weakness of gravity in context, consider the classic example of the hydrogen atom: for the electromagnetic force between the proton and electron to be as small as the gravitational force they experience in the atom, they would have to



*Si Globorum duorum in se mutuo
gravitantium materia undique,
in regionibus quæ à centrīs equaliter
nubus quæ à centrīs equaliter distant,
homogenea sit: erit pondus Globi
alterutrius in alterum reciprocè ut
quadratum distantie inter centra.*

Figure 1 Gravity, past and present. In 1798, Henry Cavendish¹ used a torsion balance (left), which he had inherited from the Rev. John Michell, to determine the gravitational constant, G . Now Long *et al.*³ have devised a high-frequency resonator (inset) to explore the gravitational interaction on previously unexplored scales. Neither Cavendish nor Long *et al.* found any deviation from Newton's universal law of gravitation, set down in 1686 in his *Philosophiæ Naturalis Principia Mathematica*, and rendered here in its original Latin form.

be separated by about 2.5 million kilometres — roughly six times the distance between the Earth and the Moon.

Expressed another way, in any gravitational experiment the 'cancellation' of the electromagnetic interaction between test masses must be at the level of roughly one part in 10^{40} to leave any sensitivity to gravity — not an easy task on short distance scales, as local charge inhomogeneities and magnetic impurities in the materials of the experiment quickly become important. A careful analysis of subtle systematic effects is crucial for any such measurement.

Elegant experiments such as that of Long *et al.*³ have a broad appeal. Cosmologists and high-energy-physics theorists, for example, are interested in the short-range properties of gravity, and its theoretical aspects present at least as many difficulties as those encountered in the laboratory. Despite years of effort, it has not been possible to devise a quantum theory of gravity, even though most theoretical physicists believe that such a theory must exist to describe it in harmony

with the other three forces. Because gravity is so weak, its quantum behaviour is usually predicted to become important only at inaccessible distances, at the scale of the 'Planck length' (10^{-33} cm). It is disconcerting to many theorists that there is such a large discrepancy between the characteristic energy scale associated with this distance (10^{19} GeV) and that of the other three forces (10^3 GeV; $1 \text{ GeV} = 10^9$ electron volts). This is known as the 'hierarchy' or 'naturalness' problem.

Recently, string theories (so called because the fundamental particles are described as vibrations of one-dimensional strings)² have become the leading candidates for the successful integration of quantum mechanics and gravity. Such models require the existence of extra spatial dimensions, in addition to the three dimensions in which we live. In particular, one class of string-inspired theories⁷ attempts to solve the hierarchy problem by suggesting that gravity is just as strong as the other interactions, but that its strength is diluted because it propagates through many spatial dimensions; the

other fundamental forces are confined to our three-dimensional world, or 'brane'.

These extra dimensions would be curled up, or 'compactified', but could still be as large as a millimetre. If one were to look closely enough to begin to 'see' these large extra dimensions, gravity would behave as if it were propagating in a higher-dimensional world, and the inverse-square attraction would no longer be observed. In addition, different string-theoretical models predict as yet unseen fundamental particles that could mediate new interactions with strength comparable to that of gravity at sub-millimetre distances (the range of a possible new force would depend inversely on the particle's mass)⁸. Evidence of these new forces could also appear in short-range tests of the inverse-square law. So searching for exotic gravitational behaviour at the laboratory scale, instead of at the Planck length, could yield the first direct evidence for string theory.

The experiment by Long *et al.*³ is the latest search for deviations from the inverse-square law. Their results set the best constraints so far on any departure from that law between 10 and 100 μm , and have ruled out much — although not all — of the remaining parameter space for new forces. So far, Newton is holding his ground. Although this first-generation apparatus could not have detected any new effects that have the same strength as gravity, the

relatively high-frequency technique has advantages that may enable it eventually to probe shorter distances with higher sensitivity. For example, many sources of environmental noise, such as temperature and seismic fluctuations, have an intrinsically 'red' (or low-frequency) tendency; the high frequency of this experiment serves to suppress the effects of these disturbances.

The development of a promising technique to measure the unexplored properties of one of the fundamental forces in nature should always be welcomed, especially when the force in question is gravity. Having a 'gene pool' of experimental techniques involving scientists from many backgrounds contributes to the growth and refinement of the field as a whole. With advances in high- and low-frequency methods, we will be better able to understand and verify any surprises that gravity may hold. ■

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Ecology

The how and why of biodiversity

Kevin J. Gaston

A study of reef fish in the Indian and Pacific oceans reveals that the structures of local communities and their regional context are intricately entwined. New species spread far from an oceanic 'hotspot' of diversity.



Figure 1 Cradle of diversity: the islands (centre) of the Indonesian and Philippine region.

In the field of biodiversity, Rudyard Kipling's "six honest serving men"¹ have progressed at very different speeds. What, Who, Where and When have established much about the basic distribution patterns of life across the Earth. But How and Why have been struggling, and their difficulties have been well aired^{2,3}. The problem has not been an absence of ideas — if anything, quite the reverse. In particular, innumerable theories have been proffered to explain why there are more species in some areas than in others. But rigorous testing and discrimination among a core group of possible mechanisms has proved difficult. On page 933 of this issue⁴, Mora and colleagues give How and Why a helping hand.

The mechanisms that might drive patterns of species richness have traditionally been divided between abiotic variables, such as temperature, rainfall and geology, and biotic variables, such as competition, predation and parasitism. But it has become

increasingly apparent that an equally, if not more, critical issue may be the distinction between processes that operate at different spatial scales. Ecologists have been most comfortable considering mechanisms that operate at spatial scales similar to those at which their own senses principally function — from metres to tens or perhaps a few hundreds of metres. So most ecological studies have been, and continue to be, conducted in highly restricted areas; most experiments have changed little in unit size (although they are now almost invariably replicated) since Darwin⁵ established his 'worm stone' to determine the rates at which earthworms bury material. Although many important insights have followed, a general understanding of why local species assemblages and communities are structured in the way they are, without recourse to case-by-case contingencies, has largely remained elusive⁶.

One obvious possibility, recognized long ago, is that processes operating over much broader spatial scales — at which experiments are difficult or impossible to conduct — markedly dictate what is seen locally. A local community is assembled from a regional pool of species. The size and structure of the pool are influenced by regional processes, including the geophysical properties and history of the region (its age, geology, size and climate), and broad-scale ecological or evolutionary processes such as species migrations and invasions, speciation and regional extinction^{6,7}. These determine features of the pool, for example the total number of species, the number of individuals within each species, the size of the individuals, and their feeding groups.

Mora *et al.*⁴ now elegantly demonstrate that the structure of a local species assemblage and its regional context are indeed inseparable. Basing their analyses on almost 2,000 species of reef fish across 70 locations in the Indian and Pacific oceans, they describe three important findings.

First, most of the species that occur at these sites are also present at a centre of high diversity in the Indonesian and Philippine region (IPR); the existence of this centre is well established. Second, the structure of the local assemblages is strongly influenced by their distance from the IPR, such that as this distance increases — both latitudinally and longitudinally — so the number of species declines. Third, as the distance from the IPR increases, the likely dispersal ability of those species present also increases; sites farther from the IPR tend to comprise species with longer open-water larval stages. In short, the local assemblages of reef fish at sites in the Indian and Pacific oceans are in large part shaped by which species have been able to reach them from the IPR. On a regional scale, the patterns of species richness have likewise been shaped by how many