PERSPECTIVES: GRAVITY

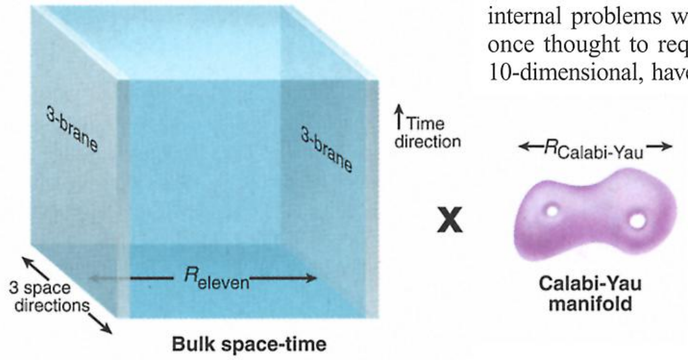
# Brane-Worlds

**Gary Gibbons**

The past year has witnessed cosmologists and particle physicists working frantically on some of the most audacious ideas yet seen in the field of gravity research. In a nutshell, the idea is to view our familiar three-dimensional expanding universe as a sheet or domain wall, called a "3-brane," that moves in a higher dimensional space-time which may turn out to be truly gigantic. The jury is still out on whether the idea really works, but some spectacular advances in string theory have made these once apparently preposterous ideas seem quite natural.

The idea that space-time has extra spatial dimensions is almost as old as Einstein's theory of relativity. Thomas Kaluza first realized in 1921 that one could obtain a unified description of gravity and electromagnetism, in which some of Einstein's equations for gravitation become Maxwell's equations of electromagnetism. In Kaluza's scheme, refined by Oskar Klein in 1926 to incorporate elementary ideas from quantum mechanics, electric charge becomes the component of momentum along the fifth dimension. Conservation of electric charge then becomes conservation of momentum; electric charge is quantized because, as in the case of the conservation of angular momentum, the extra fifth dimension curls back on itself to form a circle. As we say nowadays, the extra dimension is "compactified." No one who has worked through the mathematics of Kaluza and Klein's construction can ever forget its haunting beauty, and despite its experimental limitations—for example, it predicts a time-dependent Newton's constant—the basic idea has come to dominate all current attempts at unifying the gravitational with the electroweak and strong interactions, including the most popular, superstring theory.

As its name suggests, superstring theory describes extended objects with one spatial dimension, rather than the conventional point-like or zero-dimensional entities usually considered in particle physics. In the approximation that the strings are very short, string theories reproduce the conventional point particle models of high energy physics, such as Yang-Mills theories, which describe the electroweak and strong interactions. In addition, combined with a symmetry between bosons and fermions called supersymmetry, they provide a quantum mechanically consistent theory of gravity.




**The world of extra dimensions.** The 11-dimensional space-time of Horava and Witten (*6*). Six dimensions are curled up to form a Calabi-Yau manifold of characteristic scale $R_{Calabi\text{-}Yau}$. The remaining four spatial dimensions contain two three-dimensional mirror planes called 3-branes, separated by $R_{eleven}$. Associated with every point on the 3-brane (**left**) is a very small Calabi-Yau manifold (**right**). New developments suggest that $R_{eleven}$ could be as large as a millimeter. Alternatively, Randall and Sundrum (*9*) suggest that the universe may contain only one 3-brane in an infinitely large universe.

It used to be thought that superstrings are only consistent in 10-dimensional space times—nine spatial dimensions and one time dimension. Until very recently, superstring theory assumed that in addition to the familiar four dimensions of space and time, six compactified dimensions form a six-dimensional closed surface called a Calabi-Yau manifold (*1*). This manifold, a sort of a higher dimensional analog of a pretzel (see the figure), has a characteristic scale $R_{Calabi\text{-}Yau}$ that, to avoid conflict with our ability to probe the extra dimensions experimentally, is assumed to be small. In fact, it was assumed that it was very small, typically about $10^{-33}$ cm, the characteristic Planck length of quantum gravity. This is of course very much smaller than the smallest scales probed by electroweak particle physics experiments (about $10^{-17}$ cm). Moreover, cosmologists who tried to explain observations at the Hubble radius ($10^{28}$ cm) in terms of the behavior of the universe when it was only several Planck lengths in size, either ignored or had little success with string theory. Not surprisingly, therefore, the Calabi-Yau scheme has remained poorly integrated with the world view of phenomenological particle physicists and Big Bang cosmologists.

Recently, however, things have started to change. New ideas have emerged that are closely linked to the hierarchy problem of particle physics, that is the discrepancy between the scale of electroweak interactions ($10^{-17}$ cm) and those of Grand-Unification ($10^{-28}$ cm). According to these new ideas, the compactification size may be much larger. Moreover, they suggests a radical rethinking of our cosmological ideas.

On the more mathematical side, various internal problems with superstring theory, once thought to require space-time to be 10-dimensional, have in the past few years led to a radical reformulation, sometimes called "M-Theory," in which the theory is cast in an 11-dimensional form first given approximately in (*2*). Theorists had tried for many years to obtain a unified theory starting from 11 space-time dimensions. The problem was that both superstring theory and supergravity theories were incomplete. Theorists speculated that one should also include two-dimensional extended objects—membranes—in the picture. But why stop at two dimensions? For 10 spatial dimensions (11 space-time dimensions when we include time), one may have $p$-dimensional extended objects, or $p$-branes (*3*), with $p$ = 2, 3, …., 9. The recent radical reformulation of string theory incorporates all manner of $p$-branes, after Polchinski (*4*) showed how a particular type of brane (called "Dirichlet" branes) could be interpreted as the end points of so-called fundamental strings.

Other theoretical advances in string theory connected with strong-weak coupling dualities (*5*) have meanwhile lead to astonishing progress in our understanding of Quantum Yang-Mills theory. The basic idea behind dualities is that two apparently different theories, for example, formulated in different dimensions, may be closely related, if not identical. Horava and Witten (*6*) were able to provide the missing link between the 10-dimensional Calabi-Yau picture and the 11-dimensional space-time described above (*2*). An 11th direction is added along which mirror planes are placed at equal distance $R_{eleven}$ apart (see the fig-

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ure). $R_{eleven}$ is at least an order of magnitude bigger than $R_{Calabi\text{-}Yau}$ and may indeed be much larger. If we disregard the tiny six-dimensional Calabi-Yau manifold, the remaining five-dimensional space-time contains two flat mirror planes and closely resembles the ideas of Kaluza and Klein. In fact each mirror plane is a static 3-brane, one of which is our world and the other the world of what phenomenologists call the "hidden sector," the world of matter which interacts only weakly with our own, essentially via gravitational forces.

This static compactification model of Horava and Witten has come to replace the older model of Candelas, Horowitz, Strominger, and Witten (*1*) but it still has its limitations. Nevertheless, the basic idea that at least some of the extra dimensions could be quite large has caught on, together with the suggestion (*7*, *8*) that the basic length scale of quantum gravity, which hitherto has been equated to Planck's constant or to the slightly smaller length scale $R_{String}$ of superstring theory, may be much larger, more like the electroweak scale of $10^{-17}$ cm. In principle this could allow extra dimensions approaching a millimeter! The string scale and the size of the extra dimensions and Newton's constant are related by a simple ratio. An experimental limitation on the scale of the extra dimension now arises from the accuracy with which gravity obeys the inverse square law.

Even more radically, Randall and Sundrum have recently revived the old dream that one may be able to dispense with the compactification hypothesis altogether and contemplate our universe as an isolated 3-brane moving in an infinitely large spacetime (*9*). Randall and Sundrum's five-dimensional universe still has a small characteristic radius curvature, but their universe is truly infinite in all four spatial dimensions. The matter of which we are made up is confined to the 3-brane, rather like beads on a wire. Gravity acts in all dimensions but one of the achievements of Randall and Sundrum was to show that gravity can act in the correct way in our three-dimensional world. Before their work, no one believed that such a model was consistent with Newton's conventional inverse square law for the gravitational force, but Randall and Sundrum appear to have convinced most of their critics on this score.

Much needs to be done to produce a completely satisfactory cosmology. But Randall and Sundrum and the many others currently working in this field have clearly demonstrated that brane-world scenarios using small extra dimensions make testable predictions, both for nucleosynthesis during the Big Bang and for the existence of new particles, for cosmologists and phenomenologists to refute or confirm.

**References and Notes**

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PERSPECTIVES: EPIDEMIOLOGY

# Tracing the Origins of *Salmonella* Outbreaks

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In the 1980s, health officials in Europe and the Americas noted a considerable increase in human food-borne illness caused by *Salmonella enteritidis*, a pathogen found in chicken carcasses, eggs, and egg products (*1*). It has been suggested that the emergence of *S. enteritidis* as a public health problem may be the result of modern poultry farming practices and of a decline in the genetic diversity of domestic fowl (*2*). But this hypothesis does not explain why the number of humans infected with other *Salmonella* serotypes, such as *S. typhimurium*, has not increased (*3*, *4*). For example, the incidence of human infection with *S. enteritidis* has steadily increased since the 1960s, whereas the incidence of *S. typhimurium* infection has remained relatively constant (see figure, this page). It has been proposed that the *S. enteritidis* epidemic could be caused by clonal expansion of a single, more virulent *S. enteritidis* isolate. However, the observation that human *Salmonella* cases in Europe and the United States are associated with different *S. enteritidis* isolates does not support this notion.

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Through a retrospective analysis of epidemiological surveys, we now put forward the hypothesis that the epidemic of salmonellosis in humans due to *S. enteritidis* was triggered by this *Salmonella* serotype filling the ecological niche vacated by the avian *Salmonella* pathogens *S. pullorum* and *S. gallinarum*. Retrospective analysis revealed that *S. enteritidis* became established in poultry flocks in the 1960s, which coincided with the eradication of the avian *Salmonella* pathogens from do-

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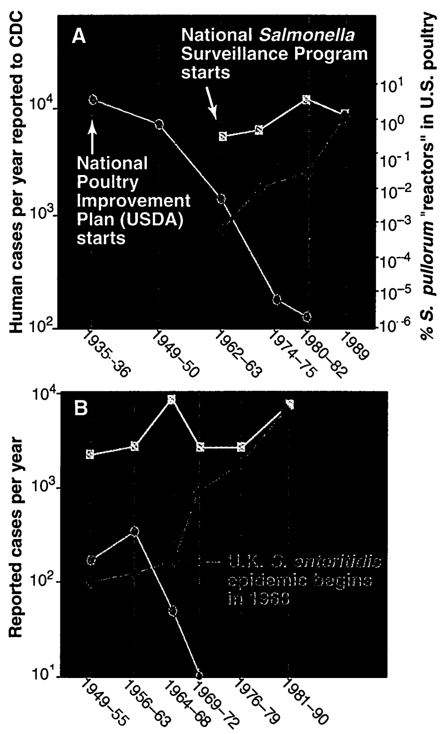


**Secrets of *Salmonella* serotypes.** Prevalence of *Salmonella* serotypes in humans and poultry in the United States (**A**) and in England and Wales (**B**). Circles show the percentage (A) or incidence (B) of domestic poultry infected with *S. pullorum* (*17*, *18*). Squares and diamonds show the numbers of human cases of food-borne illness caused by *S. typhimurium* or *S. enteritidis*, respectively (*3*, *8*, *9*, *19*).