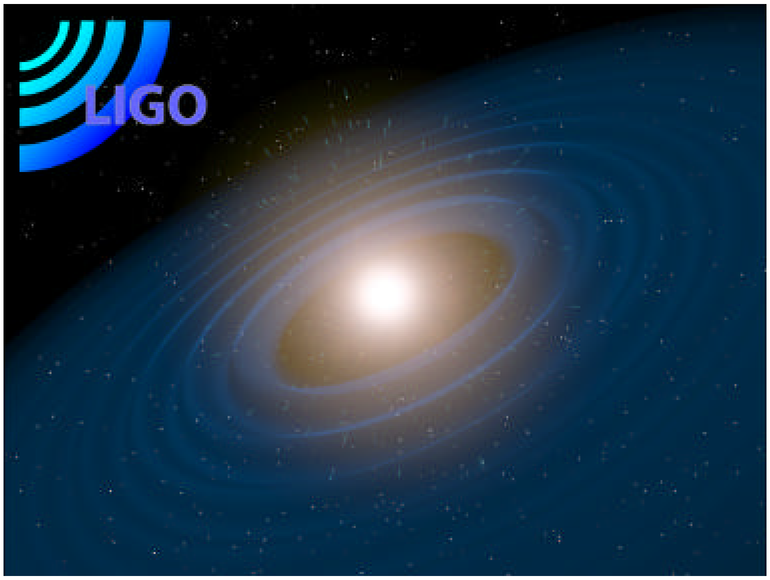
LIGO: A New Window on the Universe

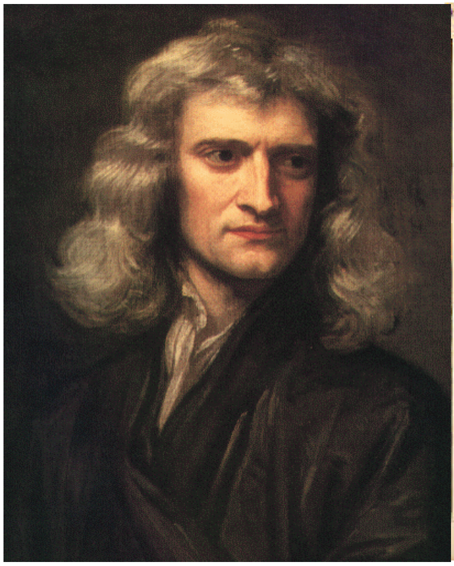
LIGO-G030031-00-M

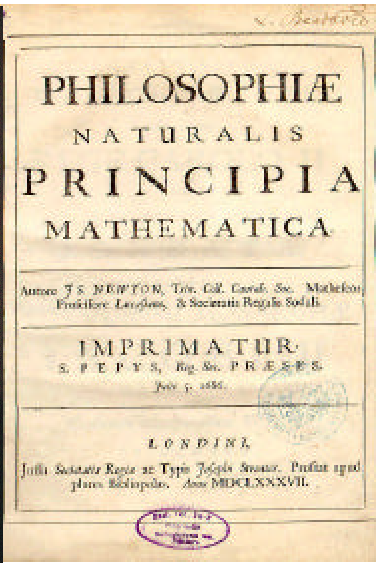
Rita Colwell, NSF



Good afternoon and welcome to what may be the weightiest event of the entire annual meeting. Our subject today is gravity – the force that is always with you.

Gravity has been studied with intense interest ever since the first proto-human fell on his duff. Of the four fundamental forces of nature, it is the one most palpably felt in our daily lives. And it was the first to be described mathematically, in Isaac Newton's conceptual triumph.





PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

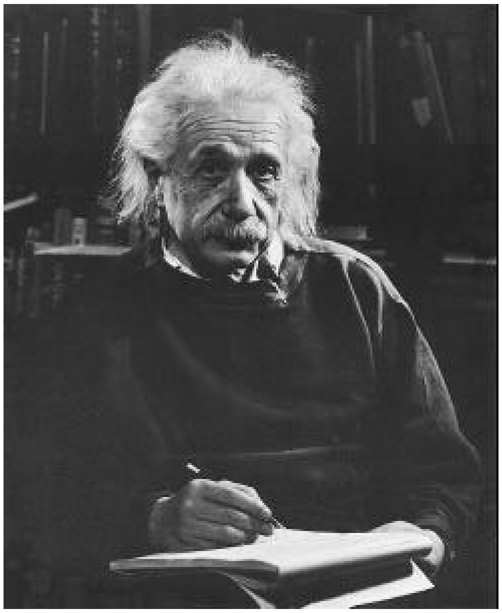
Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

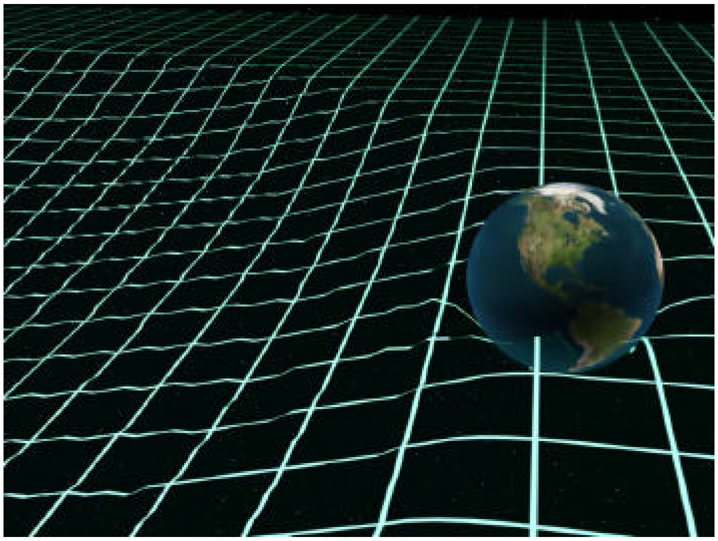
LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

It is safe to say that very few products of human intellect have served us so well or so dependably as the notion that gravitational force between any two objects varies directly in proportion to the product of the masses, and inversely to the square of the distance between them.

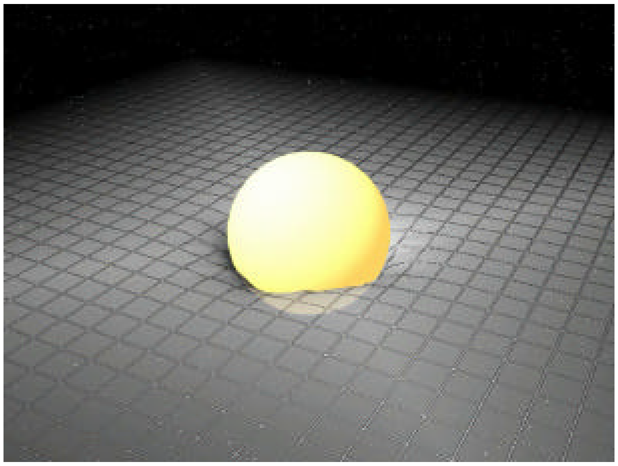
And yet, here at the dawn of the 21st century, nearly 350 years after Newton's epochal insight, gravity remains one of the most obstinate mysteries confronting modern science. That may seem odd, since the Newtonian method works so well that it led to the discovery of Neptune and Pluto, and has sent our spacecraft to the remotest corners of the solar system with exquisite accuracy.



But Sir Isaac's grand view was displaced in 1916, with the advent of one of the most revolutionary ideas since the Copernican cosmos. Gravity, according to Einstein's general theory of relativity, is not a force instantaneously communicated between masses. Instead, it is a geometric *pas de deux* jointly performed by mass and the compound entity we call spacetime.



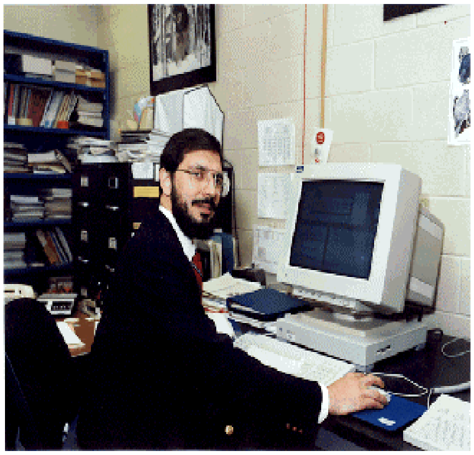
The presence of mass imposes a curvature on spacetime, while simultaneously spacetime imposes constraints on how mass can behave. Or, in John Archibald Wheeler's memorable formulation, matter tells spacetime how to curve, and spacetime tells matter how to move. Those of you who attended the lecture by Dr. Barry Barish of Caltech earlier today have already obtained a splendid overview of that concept.



Interestingly, the general theory of relativity makes another crucial prediction – the one that brings us here today. Accelerating mass should radiate gravitational *waves* – that is, ripples in spacetime – in somewhat the same way that accelerating charges give off electromagnetic radiation.

A stationary mass will not produce these waves; nor will a mass, no matter how huge, that is traveling at a constant velocity. But in theory, acceleration of a sufficiently large celestial mass will generate ripples that should be detectable on Earth – although drastically attenuated by distance. And, indeed, although no one has yet observed a gravitational wave directly, we have excellent reason to believe that they exist and function as Einstein described.

Gravitational waves, he predicted, should carry off some energy from a dynamic massive system, such as two stars that orbit one another in a “binary” arrangement. In 1974, Russell Hulse {rhymes with pulse} and Joseph Taylor, using the Arecibo radio telescope in Puerto Rico, discovered the first binary pulsar system. They also discovered that the orbital period was decreasing: That is, the two stars are rotating faster and faster around one another (well, faster by 75 one-millionths of a second per year), presumably because gravitational waves emitted by the system are draining off a bit of its energy.

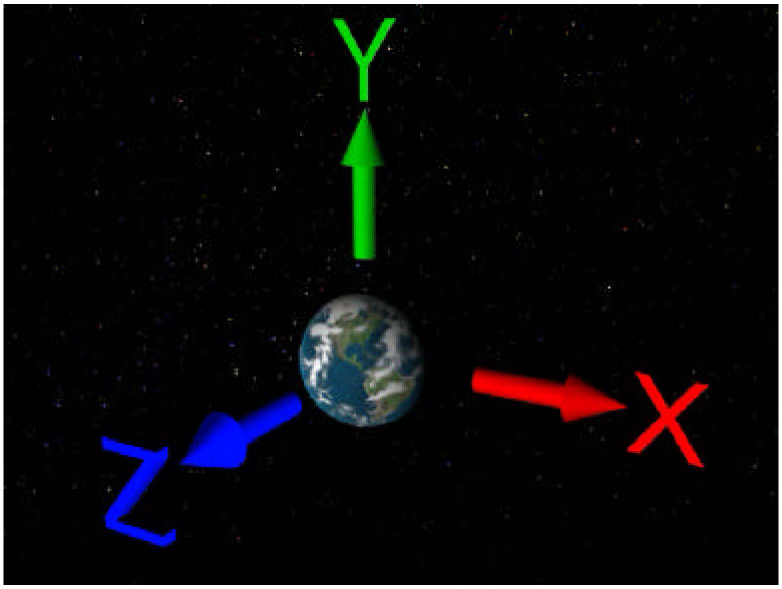


Russell Hulse and Joseph Taylor

Hulse and Taylor’s findings agreed with the theoretically calculated value to an accuracy of 99.5 percent. The pair won the Nobel Prize in Physics in 1993 for their work.

But long before that discovery, physicists were pondering ways to detect gravity waves on Earth. In the late 1950s, Joseph Weber of the University of Maryland pioneered the idea that the peculiar nature of the waves could be made measurable by their effect on large test masses.

Gravity waves affect the shape of spacetime on axes that are transverse to the direction of the waves' propagation. That is, if a wave is moving on the z axis of a coordinate system – in this illustration, coming out of the screen – then the effects will be felt as an alternating extension and compression of space on the x and y coordinates as the wave passes through.



Weber used one-ton suspended aluminum bars and piezoelectric transducers to measure strain in an attempt to detect the passage of waves through two test masses 1,000 kilometers apart. The results, though intriguing, were incon-clusive. Among other things, they indicated an effect a couple orders of magnitude larger than theory predicts – which is, to say the least, not much.

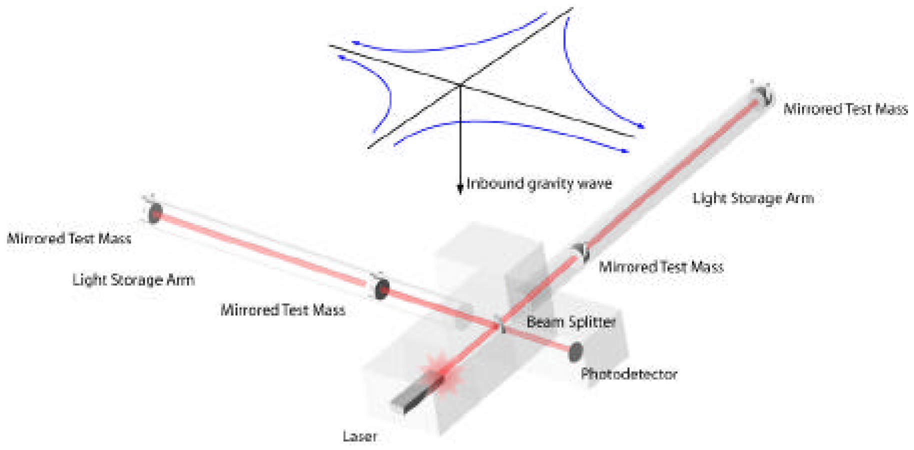
Unlike electromagnetic waves, gravity waves are neither scattered nor absorbed by interstellar dust or other celestial debris. But their strength does fall off inversely with distance.

To understand how minuscule the effect is on astronomical scales, consider this: The gravitational signature from the inspiral of two neutron stars at the center of our galaxy – each in the range of 1.4 solar masses – would amount to a dimensional change in a test mass on Earth of about one part in 10 to the minus 21. [10^{-21}] That is, one part in a billion trillion.

So, even in a test frame several kilometers long, such as LIGO's, the change in size would amount to about 10 to the minus 18 meter. [10^{-18} m] That's about 10 million times less than the diameter of a respectable atom. In fact, it's a thousand times smaller than a proton.

Still, as you will hear in the succeeding presentations, distortions on that scale can be detected through sophisticated optical interferometry. Weber and his coworker Robert Forward floated the idea about 30 years ago. By the mid-1970s, trailblazing researchers such as Ray Weiss of MIT and others had brought their ideas for interference-based detectors to NSF, which has traditionally been the primary sponsor of ground-based gravitational research – and, indeed, for numerous high-risk projects at the very frontier of understanding. The Foundation became an essential catalyst for encouraging the community to recognize the extraordinary potential of interferometric detection to produce the sensitive measurements.

The result became a plan for the Laser Interferometry Gravitational-Wave Observatory, or LIGO, which Dr. Weiss will explain in his presentation. In 1984, the Foundation deemed the proposal ready for planning and feasibility studies.



At least two detectors, separated by a considerable distance and located within quite different geophysical environments, would be necessary to discern concurrently the faint signal from the cacophony of background noise. The final design called for an L-shaped configuration with an arm length of 4 kilometers.

After examination of 19 potential sites in 17 states, construction began in Hanford, Washington and Livingston, Louisiana during the 1990s. In a tour-de-force of science and engineering, the NSF-Caltech-MIT consortium brought the ambitious and unprecedented project in on budget and on schedule. By last year, the LIGO interferometers, although still in a commissioning phase, became the most sensitive gravitational wave detectors on Earth. This prompted the LIGO researchers to undertake their first scientific data run, and today Albert Lazzarini of Caltech will present the very first scientific results from LIGO, marking the beginning of LIGO's search for gravitational waves.

Finally, David Shoemaker of MIT will give you the prospect for the future development of this facility and its plans for ever-evolving technological improvements and increased scientific reach. LIGO, after all, is not simply a masterpiece of instrumentation and design. It is also a new kind of observatory that may reveal unprecedented views of astrophysical phenomena inaccessible by other means.

And, of course, it is ultimately intended to reach the absolute limits of Earth-based detection. And so even after the first detection of gravity waves, we expect the LIGO team to keep making waves for many years to come.